Techno-economic analysis and life cycle assessment (LCA) of biomass gasification for power generation

Gabor Olejarz

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Dr. Ana Filipa da Silva Ferreira
Dr. Abel Martins Rodrigues

Examination Committee

Chairperson: Prof. Francisco Manuel da Silva Lemos
Supervisor: Dr. Ana Filipa da Silva Ferreira
Member of the Committee: Dr. Raquel Inês Segurado Correia Lopes da Silva

December 2023

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisors from Instituto Superior Técnico (IST), Dr. Ana Filipa da Silva Ferreira and Dr. Abel Martins Rodrigues, for all the guidance and expertise they shared with me during this Master's Thesis. I would also like to show my appreciation for my supervisor from my home university, Dr. Marcin Landrat, who provided me with remote access to SimaPro software at The Silesian University of Technology (SUT). Finally, I would like to extend my sincere thanks to Luís Filipe Do Carmo Calado for sharing with me all the necessary data from measurements performed in the laboratory at Instituto Politécnico de Portalegre (IPP) and for his helpful attitude.

ABSTRACT

Environmentally friendly alternatives are under investigation because of the rising negative consequences of climate change, which are caused, among other things, by greenhouse gas (GHG) emissions from fossil fuel-based electricity production. Biomass gasification is a promising technology for fossil fuel phase-out due to biomass diversity, accessibility and dispatchability. Through a Life Cycle Assessment (LCA) and Techno-economic analysis (TEA), this study evaluates the environmental impact, economic viability, and technical challenges of the gasification process of various biomass feedstocks and utilization of produced syngas for power generation based on experimental data. The study investigated three biomasses gasification (olive pomace, miscanthus and pine) under two reactor types (fixed bed and fluidized bed). Among analysed biomasses, the olive pomace is the most environmentally friendly feedstock. It is not only the least harmful but also the most economically attractive and contributes to waste stream mitigation from the olive oil industry. However, the Levelized Cost of Electricity (LCOE) is higher than alternative renewable solutions on the market. Moreover, there are still a few challenges to large-scale implementation, and more research needs to be done in this direction.

Keywords: Life Cycle Assessment (LCA); Techno-economic analysis (TEA); Biomass Gasification; Olive pomace; Miscanthus; Pine.

RESUMO

Devido às crescentes consequências relativamente às alterações climáticas, que são causadas, entre outras coisas, pelas emissões de gases com efeito de estufa (GEE) provenientes da produção de electricidade baseada em combustíveis fósseis, têm vinda a ser estudadas alternativas amigas do ambiente. A gaseificação da biomassa é uma tecnologia promissora para eliminação progressiva dos combustíveis fósseis devido à diversidade, acessibilidade e capacidade de despacho da biomassa. Através de uma Avaliação do ciclo de vida (ACV) e de uma Análise técnico-económica (ATE), este estudo avalia o impacto ambiental, a viabilidade económica e os desafios técnicos do processo de gaseificação de várias matérias-primas de biomassa e a utilização do gás de síntese produzido para a produção de energia com base em dados experimentais. O estudo investigou a gaseificação de três biomassas (bagaço de azeitona, miscanthus e pinho) em dois tipos de reactores (leito fixo e leito fluidizado). Entre as biomassas analisadas, o bagaço de azeitona é a matéria-prima mais amiga do ambiente. Não é apenas a menos nociva, mas também a mais atractiva do ponto de vista económico e contribui para a mitigação do fluxo de resíduos da indústria do azeite. No entanto, o custo nivelado da eletricidade (LCOE) é superior ao das soluções renováveis alternativas existentes no mercado. Além disso, existem ainda alguns desafios à implementação em larga escala, sendo necessário desenvolver mais investigação neste sentido.

Palavras-chave: Avaliação do ciclo de vida (ACV); Análise técnico-económica (ATE); Gaseificação de biomassa; Bagaço de azeitona; Miscanthus; Pinho.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The critical threat to humanity is climate change driven by greenhouse gas (GHG) emissions associated among others with power generation. It has already changed the environment in which people live [1] and it continues by degrading water quality and causing extreme weather events such as catastrophic flooding, droughts, and rising sea levels. Climate change puts the world's food supply at risk since crops are sensitive to climate fluctuations, which give lower yields and variability in agricultural production [2]. Climate change is also one of the key drivers of migration [3], and according to the Institute for Economics & Peace (IEP), about 1.2 billion people may be involved in climate migration by 2050 [4].

To counter severe climate change activities, in December 2016, 195 countries pledged to work together to combat climate change by signing the Paris Agreement [5]. For this reason, the European Union Commission proposed the 2030 climate and energy framework, which incorporates EU-wide targets and policy objectives for 2021 to 2030, as a component of the European Green Deal. The primary goals for 2030 are to reduce greenhouse gas emissions by at least 40% (compared to 1990 levels), increase energy efficiency by at least 32.5%, and have at least 32% share of renewable energy [6].

The four main categories of renewable energy sources are solar, wind, hydropower, and biomass [7]. Regarding diversity, accessibility, and sustainability, biomass is one of the most important renewable energy sources [8]. Biomass can benefit the overall operation of the energy system by providing stable, dispatchable power that complements the high levels of output from variable sources like solar PV and wind. In most cases, electricity generation is with biomass feedstocks such as plantation wood, forestry residue, agricultural byproducts such as bagasse, pelletized wood, and organic wastes [9]. However, biomass is difficult to store, handle and transport. Therefore, it is usually converted into gas or liquid fuel form [10] through physicochemical, biochemical, or thermochemical processes [8]. The most common thermochemical processes are direct combustion, pyrolysis, and gasification, whereas fermentation and anaerobic digestion belong to the biochemical conversion methods [11].

Nevertheless, to develop a sustainable energy system, it is necessary to undertake comprehensive analyses that cover technical, economic, and environmental considerations [12]. The Life Cycle Assessment (LCA) methodology stands as a globally recognized and widely accepted approach for evaluating the environmental impacts of products and processes [13]. Meanwhile, when it comes to assessing the technical and economic feasibility of conceptual process designs, industries commonly rely on the Techno-economic analysis (TEA) [12], [14].

The objective of this study is to assess, through LCA, the potential environmental impacts of three different types of biomasses through gasification within two different reactors for electricity generation and through TEA their economic feasibility based on the experimental data acquired with the collaboration of Valoriza of Instituto Politécnico de Portalegre (IPP).

1.1. Biomass sources

Biomass originates from living organisms such as plants and animals. It is a renewable source because it reproduces (e.g. plant growing), and contrary to finite fossil fuels, does not take millions of years to form. Biomass includes a broad materials range, from small grasses to tall trees and tiny insects to significant animal waste. Biomass can be classified in various ways, but within this study it decided to classify based on the common sources of biomass: Agricultural, Forest, Municipal, Energy Crops and Biological [10].

1.1.1. Agricultural biomass

Agricultural biomass can be categorized into field residues and process residues. Field residues consist of the leftover parts of a crop after it has been harvested (e.g. stalks, leaves, stems, seed pods). While process residues are the residue from the transformation of the crop into valuable products (e.g. husks, bagasse, seeds, leaves, stem, straw, stalk, shell, pulp, stubble, peel, and roots) [15].

The availability of agricultural biomass fluctuates seasonally, and the timing of harvest varies depending on when crops are planted. As a result, this leads to irregular monthly availability of crop residues [16].

1.1.2. Forest biomass

Forest biomass can be categorized into whole-tree biomass and forest residues. Whole-tree biomass refers to intentional tree harvesting specifically for biomass purposes, while forest residues result from timber logging activities (limbs, tops, culled trees, and other non-merchantable tree components). Harvesting surplus biomass from forests mitigates fire and pest risks, supports restoration, and enhances forest vitality without adverse effects on the ecosystem's structure and function [17].

Another type of forest origin biomass is a wood waste from various wood processing sectors [10], including sawmills, plywood mills, furniture making, flooring production, and more. These industries generally accumulate wood waste on sites (sawmills and plywood mills). The amount of material created varies in each industry, depending on the raw materials used and the characteristics of the final products [18].

1.1.3. Municipal biomass

Biomass of Municipal source include Municipal Solid Waste (MSW), sewage sludge, and refuse-derived fuel (RDF) [10].

Municipal solid waste (MSW) is an important source of waste biomass, and much of it comes from plant origins like food scraps, lawn clippings, leaves, and papers. Other components of MSW like plastics, glass, and metals are not considered biomass [10].

Refuse Derived Fuel (RDF) is generated using the combustible components found in Municipal Solid Waste (MSW) [10]. The production process involves shredding and sorting to eliminate all non-combustible materials like glass, metal, and stone, which is done using a series of mechanical processes [19].

Sewage sludge is a thick residue formed during wastewater treatment. It contains human faeces, fat, oil, and food waste. Due to its valuable organic material and essential nutrients such as nitrogen and phosphorus, it can be used as fertilizer or soil enhancer. However, it may contain impurities for instance heavy metals, chemicals, or pathogens [10], [20].

1.1.4. Energy crops biomass

An energy crop is a plant grown in agriculture exclusively or primarily to produce biomass for energy purposes rather than food or other reasons. Energy crops typically include perennial grasses and short-rotation coppice plants unsuitable for human or animal consumption [21], but also corn, soybean, canola, and other oily plants [10].

Perennial grasses such as switchgrass, miscanthus, bamboo, sweet sorghum, and others are harvested annually after two to three years of growth when reaching maximum productivity, while short-rotation woody crops like hybrid poplar and willow, silver maple, green ash, black walnut, and more are fast-growing hardwood trees harvested within five to eight years after planting [17].

1.1.5. Biological biomass

Under this biomass source one can distinguish animal waste and aquatic species [10]. Animal waste is produced in animal husbandry, primarily livestock manure. Traditionally used as fertilizer or spread on agricultural land, but due to stricter environmental regulations, interest has shifted to waste-to-energy conversion [18].

Aquatic species comprise a wide range of photosynthetic organisms known as algae, totalling over 72 500 species. The 20% of all algae species are larger multicellular macroalgae, ranging from a few millimetres up to 70 meters in length. In contrast, the remaining 80% consists of microalgae, which are unicellular in nature [22].

1.2. Biomass conversion technologies

Biomass, unlike gases or liquids, is not easily manageable, storable, or transportable due to its bulkiness and low energy density. It contributes to a significant incentive for solid biomass transformation into liquid and gaseous fuels. Such conversion is achieved through either biochemical or thermochemical conversion [10]. Factors such as the type of biomass, its availability and quality, the desired end-products, economic considerations, environmental concerns, and project-specific aspects influence the choice of biomass conversion technology [23].

1.2.1. Biochemical conversion

Biochemical biomass conversion technologies involve enzymes, bacteria, or other microbes usage to decompose biomasses organic material [23] into valuable products such as hydrogen, biogas, various alcohols (e.g., ethanol, butanol), organic acids, and more. The biochemical conversion technologies are moderate, clean, pure, and efficient [24] but relatively slow [10]. The fundamental biochemical conversion technologies include anaerobic digestion, aerobic digestion, and fermentation.

Anaerobic digestion

Anaerobic digestion is a natural biological process in which naturally existing bacteria break down biomass in the absence of oxygen [25]. This process produces two products: digestate and biogas consisting of CH_4, CO_2, and trace gases such as N_2 and H_2S. The anaerobic digestion process takes four stages. During the first step (hydrolysis), complex organic molecules get broken down into simpler, soluble compounds. Then, within acidogenesis, the acidogenic bacteria convert soluble substances into short-chain organic acids, alcohols, H_2, and CO_2. After that, under acetogenesis, higher organic acids are transformed into acetic acid and H_2 by the metabolic processes of acetogenic bacteria. As part of the last stage (methanogenesis), compounds are digested by methanogenic bacteria and transformed into CH_4 and CO_2 [23].

Aerobic digestion

Aerobic digestion, also known as composting, is a biochemical breakdown of biomass in the presence of oxygen. It uses microorganisms that access oxygen from the air and produce CO_2, heat, and a solid digestate [10] called compost, which is rich in nutrients and hygienically safe. Aerobic digestion consists of four phases. During the first initial (mesophilic) phase (10–42°C), the temperature rapidly increases, initiating organic matter decomposition. Then, due to the extensive metabolic activities of microorganisms, high temperatures prolong (thermophilic phase at 45–70°C), which later decreases (intermediate mesophilic phase at 65–50°C) allowing heat-resistant microbes to re-establish. As temperature drops, the finishing phase (50–23°C) activates, and organic matter and heat production stabilize as temperatures still decrease [26].

Fermentation

Fermentation is a process that uses microorganisms like fungi, yeast, or bacteria to convert sugars from biomass into biofuels like ethanol, butanol, acetone, iso-butanol, lipids, and valuable biochemicals such as organic acids [27]. The conversion of lignocellulosic biomass is more difficult than sugar or starch crops, because of the presence of polysaccharide molecules which require acid or enzymatic hydrolysis before the resulting sugars can be converted to alcohol [23].

1.2.2. Thermochemical conversion

Thermochemical conversion involves the usage of high temperatures to break down the organic matter in biomass, resulting in the production of carbon-rich solids (biochar), condensable vapours (bio-oil, tar), and gaseous products. The thermochemical conversion methods differ in the oxygen content and temperature range within the process, which determines the predominant product outcome [28]. In essence, any biomass can serve as a suitable feedstock for these processes [23]. The essential thermochemical conversion technologies include combustion, pyrolysis, and gasification.

Combustion

Combustion process is a high-temperature (700°C - 1400°C) exothermic oxidation of hydrocarbons in biomass under oxygen-rich ambience. In the context of biomass feedstock, this method is non-selective and may be applied directly to the entire biomass to oxidize it into two main components H_2O and CO_2. In certain rural areas of the world, the combustion process is utilized to supply heat for cooking and warming, but industry employs it to generate heat and electricity [10]. It consists of four stages: drying, pyrolysis, volatile combustion, and char combustion. The process depends on the feedstock properties, particle size, temperature, and ambient conditions. Biomass contains a higher volatile matter content (approximately 70-80%), more oxygen and impurities such as S and N_2 compared to fossil fuels. These factors impact its thermal decomposition and result in SO_X and NO_X emissions. High inorganic element levels in biomass can lead to operational issues like agglomeration, deposition, fouling, sintering, corrosion, or erosion. Ensuring proper air supply is crucial due to the rapid release of volatile matter and lower ignition temperature in biomass. Furthermore, improper air supply can lead to incomplete combustion, which leads to unwanted CO, CH_4, and particulate matter production. Boiler designs and combustion parameters are selected based on biomass properties for optimal efficiency [28], [29]. Biomass can be used as an independent fuel or a complement to fossil fuels in a process known as co-firing [10].

Pyrolysis

Pyrolysis is an endothermic process of biomass decomposing into gas, liquid, and solid at elevated temperatures (300°C - 1250°C) [30] in the total absence of oxygen [10]. Pyrolysis depends on several critical factors, including temperature, pressure, heating rate, residence time, environmental conditions, and the presence of catalysts. These conditions are vital in determining pyrolysis product outcomes and adjusting them enables the desired product production. Depending on these pyrolysis conditions, the process can be categorized as fast or slow pyrolysis.

a) Fast pyrolysis

Fast pyrolysis aims to maximize bio-oil yield. The process involves high temperatures (850–1250°C), high heating rates (10–200°C/s) and short residence times (0.5–10 s). Typical yields for fast pyrolysis are 15–25 wt% biochar, 60–75 wt% for bio-oil, and 10–20 wt% for gas [30], [31].

b) Slow pyrolysis

Slow pyrolysis, also called carbonization, aims to maximize biochar yield. The process involves moderate temperatures (300–550°C), slow heating rates (0.1–0.8°C/s), and extended residence times (5–30 min) [32]. It was studied that acidic catalysts (NaCl, LiCl, KCl), elevated pressure conditions and larger particle-sized biomass with high lignin and low moisture content favour higher biochar production [30]. Typical yields of slow pyrolysis are 35 wt% for biochar, 30 wt% for bio-oil, and 35 wt% for gas [31].

Gasification

Gasification is an endothermic process that transforms solid biomass into syngas, liquids (oils and tars), and solids (biochar and ash) at elevated temperatures (700 to 1600°C) [33] under controlled oxygen-deficient conditions to prevent full combustion. In contrast to pyrolysis, gasification introduces a gasifying agent (such as air, steam, oxygen, CO_2, or a mixture) [34], initiating reactions between oxygen and carbon. The resulting syngas primarily consist of CO, H_2, CH_4, CO_2, H_2O, and N_2, influenced by biomass quality and gasification parameters. Syngas is a versatile energy source used for heat and electricity generation and serves as a feedstock for chemicals like methanol and ammonia [29].

1.3. Biomass gasification

In recent years, gasification technology has proven to be an efficient thermochemical conversion process with diverse applications, including thermal processes, power generation and Fischer-Tropsch liquid fuel production. Biomass gasification has attracted considerable attention from industrial and academic researchers thanks to its numerous advantages. With the further development of gasification technology, it is likely to play an increasingly important role in global energy and industrial markets, especially in clean power generation [13], [33].

The gasification process is complex and occurs in a gasifier at elevated temperatures and pressures. The gasifying agent comes into direct contact with the feedstock, initiating a sequence of physical and chemical reactions, usually divided into the following stages:

1. Drying (>150°C)
2. Pyrolysis (devolatilization) (150-700°C)
3. Oxidation (700-1500°C)
4. Reduction (800-1100°C)

The resulting syngas contain CO, CH_4, H_2 and a small number of other hydrocarbons such as C_2H_2, C_2H_4 and C_2H_6 and non-combustible gases such as CO_2 and N_2. During gasification, some amounts of untreated charcoal, fly ash particles and trace amounts of various species are carried along with the syngas. These impurities, including particulates, sulphides, alkali metals and heavier carbon compounds (tars), makes the gas harmful to equipment [33].

Gasification process depends on biomass characteristics (size, density, elemental composition, energy content, fixed carbon, volatile matter, ash content, and moisture content), the operating parameters (equivalence ratio, temperature, type and amount of catalyst, feed rate), oxidizing agent and gasifier type and design (fixed bed, fluidized bed, entrained flow, and plasma) [28]. Typically, biomass gasification process yields 85 wt% of gas, 5 wt% of liquids and 10 wt% of solids [35]. The process efficiency is so-called Cold Gas Efficiency (CGE) calculated with Equation 1 [10]:

$$\eta_{CGE} = \frac{\mathrm{M_{syngas}} \cdot \mathrm{LHV_{syngas}}}{\mathrm{M}_{solid\ biomass} \cdot \mathrm{LHV}_{solid\ biomass}} \tag{1}$$

where:

- $\mathrm{M_{syngas}}$ – mass of produced syngas [kg]
- $\mathrm{M}_{solid\ biomass}$ – mass of gasified solid biomass [kg]
- $\mathrm{LHV_{syngas}}$ – Lower Heating Value of syngas [MJ/kg]
- $\mathrm{LHV_{solid\ biomass}}$ – Lower Heating Value of gasified solid biomass [MJ/kg]

1.3.1. Biomass characteristics

Selecting the appropriate feedstock is crucial as the biomass composition has a wide range of changes in its physical and chemical properties. These variations significantly influence the gasification process, thereby the resulting gas composition [33]. To assess the chemical properties of feedstock, both ultimate and proximate analyses are conducted. The ultimate analysis evaluates the content of hydrogen, carbon, oxygen, nitrogen, and sulphur, while the proximate analysis assesses volatile matter, moisture, ash content, and fixed carbon [10].

Biomass with higher carbon and oxygen content yields a higher percentage of combustibles in product gas [36]. On the other hand, biomass with high ash content may cause gasification not possible, as the oxidation temperature typically surpasses the melting point of biomass ash. It can result in slagging and subsequently blocking feed, obstructing the process [37]. Feedstocks with a high moisture content lower the reactor temperature and slow down endothermic reactions. Furthermore, it may negatively affect the handling, storage, and transportation of biomass. Therefore, advised feedstock containing <15% of moisture content [38].

Smaller particle sizes often increase the hydrogen content of the syngas generated and reduce tar creation. Due to greater surface areas and lower diffusion resistance coefficients, size reduction improves mass and heat transfer efficiency between the particles, accelerating reactions and enhancing fuel conversion and gasification efficiency [39]. Although a lower biomass particle size is beneficial, particle size reduction consumes much energy, so the particles should not be smaller than required [40]. On the other hand, larger-sized particles reduce pre-treatment energy expenditures but have difficulties with feeding, devolatilization, and overall decomposition performance, as well as higher heat resistance, resulting in more char created due to the incomplete decomposition process. Even though biomass particle size impacts gasification results, it is vital to remember that different types of gasifiers are designed to handle varying particle sizes of biomass [40], [41].

1.3.2. Operating conditions

The equivalence ratio (ER) is critical and indicates the actual air-fuel mixture ratio to the stoichiometric air-fuel ratio. Maintaining ER within the range of 0.2 to 0.3 is crucial, as low values (<0.2) lead to issues like incomplete gasification and reduced product gas heating value, while high values (>0.4) result in increased CO_2 and H_2O formation, diminishing desirable gases such as CO and H_2 [10].

Other fundamental operating conditions for gasification are temperature and pressure. Two pressure gasification variations exist: atmospheric and pressurized. Increasing the working pressure minimizes char and tar yield in syngas, which additionally is already compressed for possible future usage (engines or turbines) [42].

However, pressurized systems face challenges in feedstock loading and construction complexity, making them economically unviable for small-scale plants [38]. Temperature significantly influences gasification, impacting syngas yield, composition, tar, and char formation [34]. Higher temperatures enhance syngas yield and concentrations of CO and H_2 while decreasing CO_2, CH_4 and H_2O, improving carbon conversion efficiency and reducing tar content [42].

Catalyst usage is not obligatory, yet it offers the advantage of eliminating tar from the product gas. Tar molecules undergo decomposition into lighter counterparts and are reformed into valuable gaseous fuels (CO and H_2) on the active sites of catalysts through various simultaneous reactions (such as thermal cracking, steam reforming, dry reforming, carbon formation, water-gas shift, etc.). This process enhances the yield and heating value of the produced gas, replacing undesirable tar or soot. Catalysts fall into three categories: Earth-metal, Nickel-based, and Alkali-metal [10], [34].

1.3.3. Gasifying agents

The selection of a gasifying agent is a critical factor influencing the quantity and quality of syngas produced in gasification processes. Gasifying agents include air, oxygen, steam, carbon dioxide, and various combinations, each chosen based on the desired syngas composition and energy requirements [43].

Air is the most common gasifying agent since it is cost-effective and easily accessible. However, its high nitrogen content presents challenges, such as the need for larger equipment and more powerful fans. Additionally, it significantly reduces the heating value of the obtained syngas due to the nitrogen dilution effect. Gasification with the usage of oxygen features the highest heating value of produced syngas due to the absence of N_2. However, the need for a pure O_2 supply implicates operational costs and safety issues. On the other hand, steam as a gasifying agent increases H_2 production and reduces tar content while requiring less energy than partial oxidation with oxygen obtained from air. However, it increases energy requirements due to the endothermic nature of reactions, including the water gas shift reaction and primary and secondary steam reactions [44].

1.3.4. Types of gasifiers

Gasifiers are reactors in which gasification of biomass takes place [45]. Depending on the requirements, many types of biomass gasifier technology are available, which vary in size and design [46]. The acceptable range of reaction conditions, feedstock properties, and ash concentration differs with gasifier type [47].

Fixed bed gasifier

The fixed bed or moving bed gasifier represents one of the oldest and simplest gasification technologies, with feedstock coming down through the gasifier. Due to its uncomplicated design and operational ease, it stands as the most widely employed gasifier commercially. Those gasifiers are the most cost-effective and ideal for small-scale gasification for heat and power generation applications but are also commonly used for thermal large-scale systems. The most common fixed bed gasifier types are updraft and downdraft gasifiers (Figure 1) [46],[48].

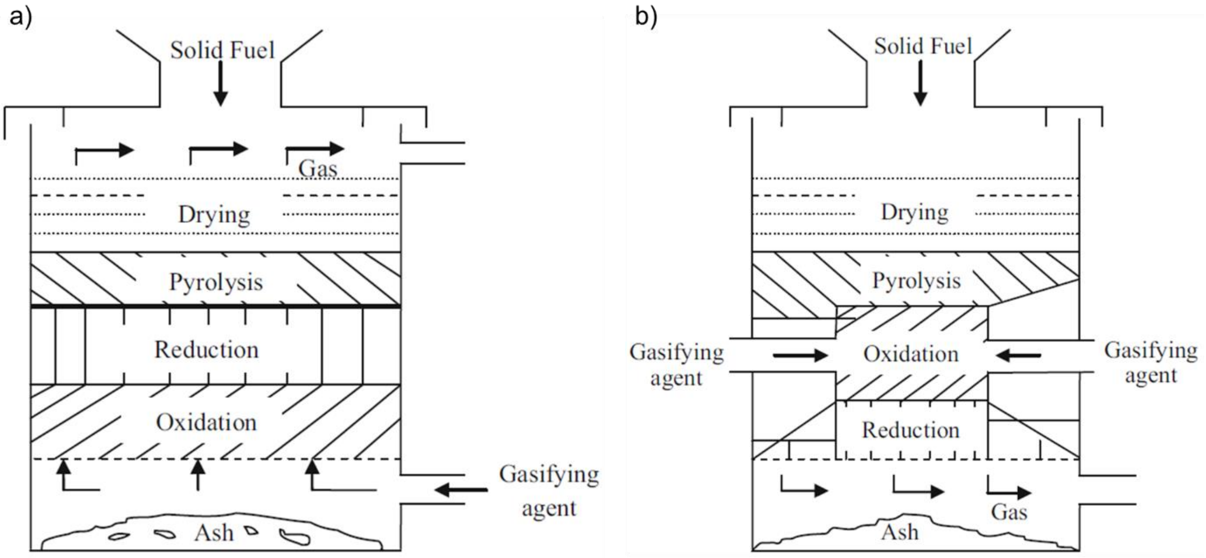

Figure 1. General scheme of fixed bed gasifier: a) updraft; b) downdraft [10].

a) Updraft gasifiers

In updraft gasifiers, the gasifying agent flows from the bottom, while the feedstock introduced is from the upper part of the reactor. It creates a counter-current contact direction, and the resulting syngas exit the reactor from the upper side. The updraft configuration offers the highest thermal efficiency, as the gas leaving the reactor has a relatively low temperature during the rapid drying process [47]. It has a low risk of slag formation and a tolerance of particle size, generally ranging from 2 to 50 mm. However, these gasifiers exhibit drawbacks, including a high concentration of tar, low syngas yield, a long start-up time, and weak reaction capability [46], [48].

b) Downdraft gasifiers

In downdraft gasifiers, the gasifying agent flows from the top or sides of the reactor, while the feedstock introduced is simultaneously from the top. It results in a co-current contact direction, and the generated syngas exit the reactor from the bottom side [8]. Downdraft gasifiers are known for their robustness, maturity, absence of scaling issues, high carbon transformation, and low tar creation [45]. However, the high-temperature gas leaving the reactor has low energy efficiency and still contains dust and ash. Downdraft gasifiers are prone to blocking, channelling, and bridging issues, making them less fuel-flexible, accepting only dense materials with a moisture content of less than 30%, and requiring homogeneous particle sizes ranging from 10 to 300 mm [47],[49],[50].

Fluidized bed gasifier

Fluidized bed gasifiers operate based on the principle of fluidization, where both the feedstock and inert bed material act like a fluid. This design ensures temperature homogeneity, leading to high efficiency and conversion rates due to rapid biomass decomposition [50]. Fluidized bed gasifiers operate in the temperature range of 800-1000ºC to minimize ash agglomeration [10]. The bed materials play a crucial role in heat storage, transferring generated energy from exothermic reactions to support endothermic reactions. While silica is a conventional choice for inert bed material, alternative solids such as sand, olivine, dolomite, and limestone with catalytic properties are under exploration to address tar-related challenges. In instances where substitution encounters mechanical resistance issues, in-bed additives like kaolin, calcium oxide, or carbonite and bauxite prove effective in mitigating tar agglomeration. Fluidized bed reactors are categorized as bubbling or circulating fluidized bed reactors (Figure 2) [41], [46].

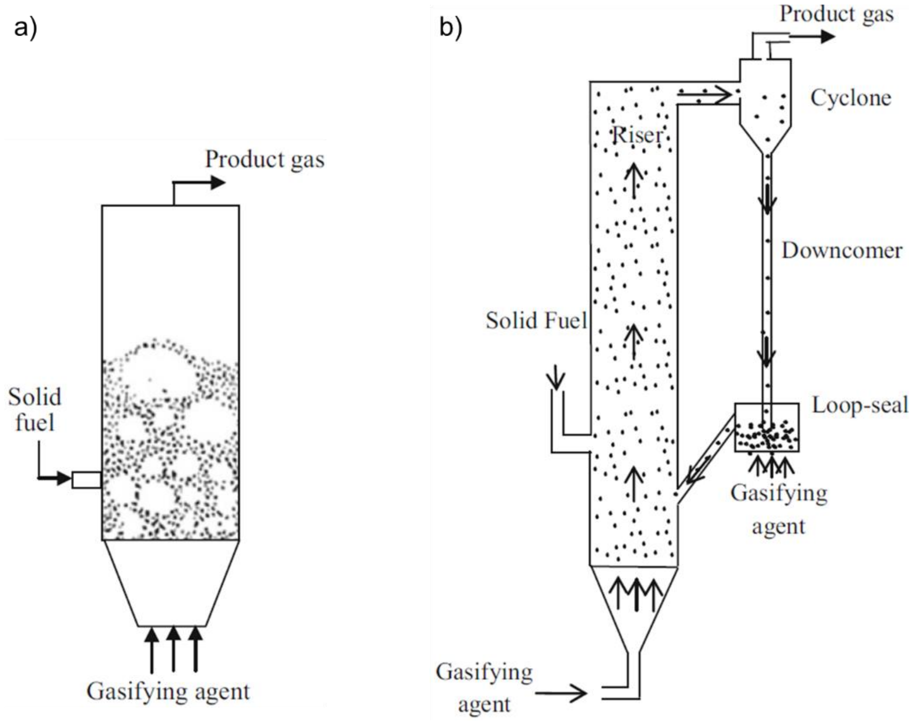

Figure 2. General scheme of fluidized bed gasifier: a) bubbling; b) circulating [10].

a) Bubbling fluidized bed gasifier

In a bubbling fluidized bed gasifier, the gasifying agent flows from the bottom of the reactor through the grate, intentionally maintaining a low velocity (<5 m/s) to create particle and bubble emulsions in the bed [38]. Solid fuel can be introduced from the top or deep inside the bed, ensuring sufficient residence time for fine particles. The gasifying agent's velocity suspends particles without expulsion, resulting in a uniform temperature distribution. Cyclone separators capture particles leaving the gasifier, which can either return to the bed or be removed as fly ash. Advantages include simple construction, easy operation, scalability, high carbon conversion efficiency, and adaptability to various feedstocks and particle sizes. However, there are feed size restrictions and high capital and operational costs. Moreover, tar formation is higher than in downdraft gasifiers when a catalyst is not used [33], [45].

b) Circulating fluidized bed gasifier

In a circulating fluidized bed gasifier, the bed material circulates continuously between the reaction tank and a cyclone separator, collecting ash while supplying bed material and char back to the reaction vessel [50]. The gasifier operates with a high velocity (typically 5-10 m/s), allowing for intense mixing leading to excellent gas-solid contact. Advantages include handling low-quality, ash-rich feedstocks, high carbon conversion efficiency with minimal tar formation, scalability, short residence time, and suitability for large-scale deployment. However, challenges include temperature gradients, dependence on fuel particle size, potential erosion, complexity, difficult regulation, high investment, and operational costs due to high gas velocities and solids recirculation, and potential safety risks [33], [45], [47].

Entrained flow gasifier

In an entrained flow gasifier, the gasifying agent, typically oxygen (O_2), is introduced along with powdered feedstock (<75 µm) at a high velocity into the reactor, whether in dry or slurry form (Figure 3). These gasifiers usually operate at high temperatures (1300-1500ºC) and pressures (20-70 bar) with a short biomass residence time of 1-5 seconds. The entrained flow reactor achieves remarkably high carbon conversion efficiency, making it well-suited for large-scale applications. The elevated temperature in this process almost entirely eliminates tar, oils, and phenols, resulting in high-quality gas yields. However, notable drawbacks include low energy efficiency and the necessity for expensive reactor materials due to high-temperature requirements, a significant need for the gasification agent, high fuel preparation costs and overall process complexity [10], [33], [38].

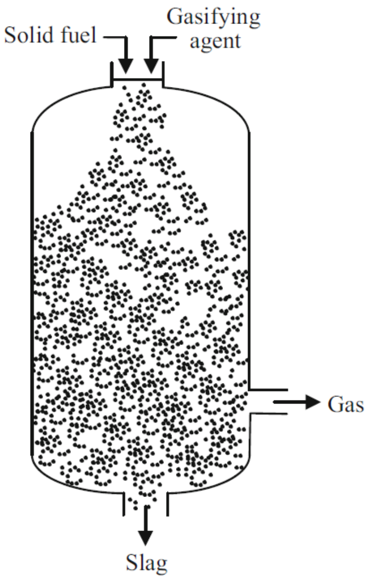

Figure 3. General scheme of entrained gasifier [10].

Plasma gasifier

In plasma gasifier, the plasma system in the form of a plasma torch or plasma arc, is positioned close to the gasifier's bottom. Feedstock is fed from the top and passes through the plasma zone, while the gasifying agent, acting as ionized gas, is introduced near the plasma system (Figure 4) [33]. Gasification occurs at extremely high temperatures, ranging from 2700 to 4500°C [10]. The intense heat in plasma gasification leads to the complete breakdown of heavy species, melting of impurities, and vitrification of the inorganic fraction into a glassy material during cooling and solidification [8], [42]. Plasma gasifiers offer advantages such as easy scalability, the production of high-purity syngas, and compatibility with a wide range of hazardous and non-hazardous feedstocks [51]. However, these systems have security vulnerabilities, maintenance challenges due to movable parts, and high investment and operational costs [45].

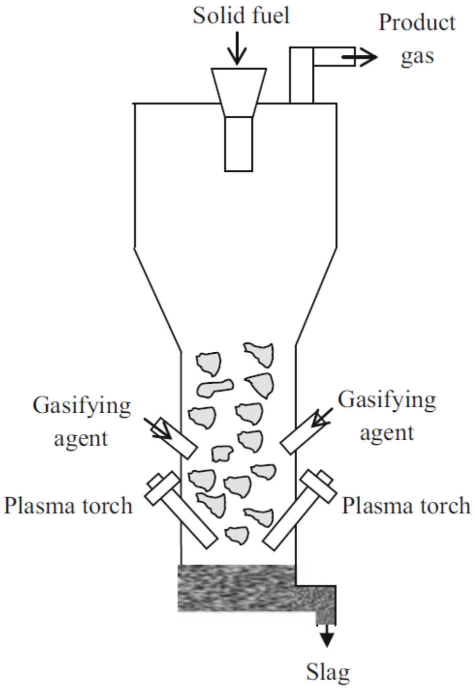

Figure 4. General scheme of plasma gasifier [10].

1.4. Life Cycle Assessment (LCA)

LCA is a comprehensive methodology to evaluate the environmental impacts of a system, process, or product throughout its entire lifecycle, from cradle to grave. This systematic analysis involves gathering and examining inputs, outputs, and associated environmental impacts at various stages, such as resource extraction, plant construction, utilization, and decommissioning. To ensure consistency and adherence the ISO 14040:2006 and ISO 14044:2006 standards provide the necessary requirements and guidelines for conducting LCA [52].

a) ISO 14040:2006

ISO 14040:2006 serves as the foundational guide for conducting a comprehensive LCA, including the definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for value choices and optional elements usage [53].

b) ISO 14044:2006

ISO 14044:2006 complements ISO 14040, providing detailed requirements and guidelines for executing a LCA including definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for value choices and optional elements usage [54].

1.4.1. LCA Softwares

Several commercial softwared are available on the market for conducting LCA. Each offers unique characteristics, including functionality, database availability, user interface, data quality management, and techniques of modelling for developing product systems. Currently main LCA software tools are: SimaPro, Sphera (GaBi), openLCA and Umberto [55].

a) Simapro

SimaPro is a widely used LCA software tool, offering a comprehensive framework. Its extensive life cycle inventory (LCI) database simplifies data collection and analysis. SimaPro allows users to customize LCA modelling to reflect industry or regional factors, generating clear and concise reports for stakeholders. It finds applications across diverse industries, helping organizations make informed decisions about their environmental impact [56].

b) Sphera (GaBi)

Sphera, formerly known as GaBi is known for its extensive environmental database, enabling customized LCA modelling. It supports the generation of tailored reports for clear communication of LCA results. It can be integrated with other sustainability tools, offering a holistic view of an organization's environmental impact. Widely used in various industries, proves to be a powerful and flexible tool for enhancing sustainability performance [57].

c) OpenLCA

OpenLCA is an open-source tool designed for LCA and sustainability evaluations. It's flexible, accommodating various impact assessment methods, making it accessible to a broad user base. OpenLCA allows for detailed assessments of sustainability performance through inventory analysis and effective communication of results [58].

d) Umberto

Umberto is a user-friendly software used for LCA and Material Flow Analyses (MFAs). It facilitates material and energy flow analyses, offering scenario analysis tools for simulating different situations. With customizable reporting and visualization features, Umberto aids in creating professional reports and visuals for communicating sustainability performance. Additionally, it provides process modelling tools for identifying efficiency improvement opportunities [59].

Utilizing Elsevier's Scopus Database, data focusing on the number of papers employing LCA through the four mentioned LCA software tools in the 2002 - 2022 timeframe was extracted (Figure 5). The analysis distinctly highlights that SimaPro is the most widely utilized tool in the scientific community. Steadily, almost every year, SimaPro maintained a share exceeding 60%, with an average of 69.7% over the past two decades. Notably, in the last few years, OpenLCA has witnessed a surge in popularity, and in 2022, it nearly caught up with Sphera (GaBi) with share of 17.4% vs. 20.9%, respectively.

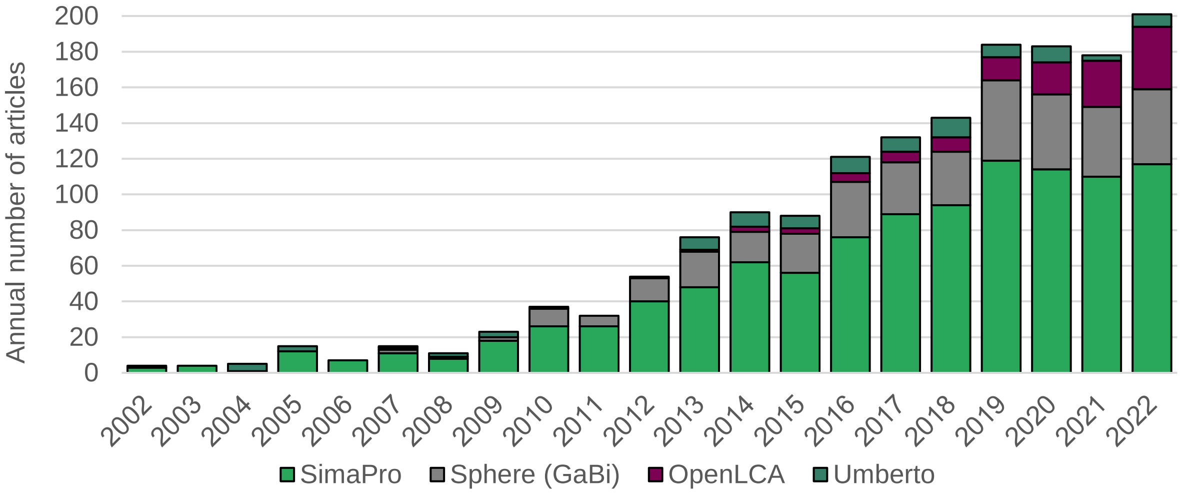

Figure 5. An annual number of LCA publications - Data retrieved from Elsevier's Scopus Database focusing on SimaPro, GaBi, openLCA and Umberto software.

1.4.2. LCA of Biomass Gasification

In recent years the interest in conducting an LCA of biomass gasification is growing. This trend can be observed in Figure 6, which consists of data extracted from Elsevier Scopus Database regarding annual papers consisting of biomass gasification LCA.

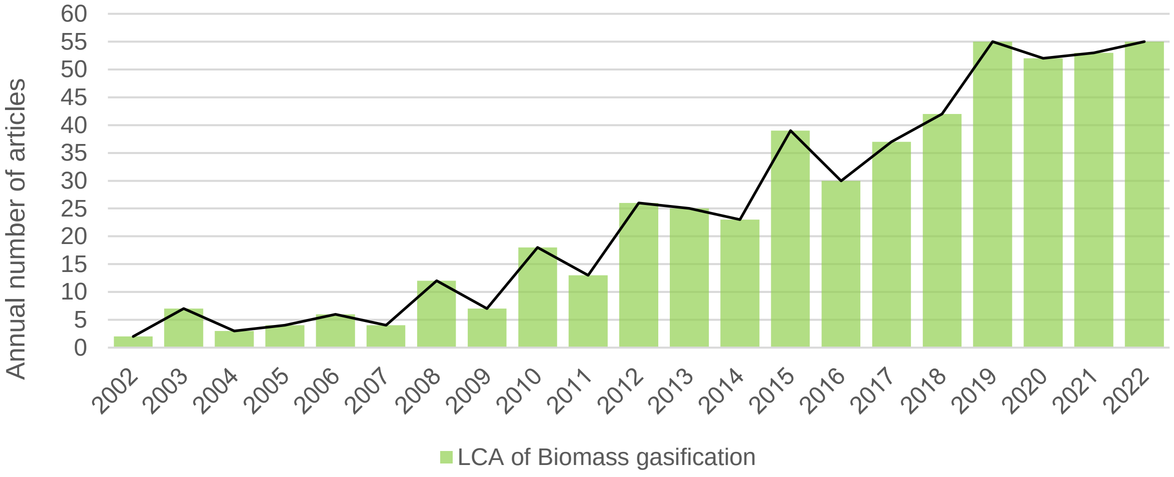

Figure 6. An annual number of LCA publications - Data retrieved from Elsevier's Scopus Database focusing biomass gasification process.

This increase in interest reflects a wider commitment to understanding the environmental impact of biomass gasification technologies to produce syngas. The following examples present some of those notable studies:

Ozturk et al. [60] which conducted an LCA in Turkey, assessing the environmental impacts of olive pomace gasification for electricity generation. The study aimed to assess overall environmental impacts through four scenarios utilizing a cradle-to-grave approach. The evaluation covered olive cultivation, pomace generation during olive oil production, gasification, gasifier construction, gas cleaning, and syngas composition. Results showed very low impact values, particularly favourable when utilizing biochar in various industries. The scenario with biochar and tar usage in another industry emerged as the most environmentally favourable, exhibiting low impact values in ozone layer depletion and global warming potential.

Balcioglu et al. [61] evaluated the life cycle environmental impacts and costs of heat and electricity generation from two potential energy crops in Turkey: poplar and miscanthus. Through LCA and life cycle costing (LCC), different bioenergy conversion pathways were explored, including direct combustion, gasification, and co-firing with lignite. The preferred option among considered pathways was combined heat and power (CHP) combustion using poplar. All bioenergy plants showed substantial reductions in global warming potential, fossil fuel depletion, and human toxicity compared to natural gas heat and grid electricity.

Nguyen & Hermansen [62] evaluated the life cycle environmental performance of miscanthus gasification for electricity production in Denmark, comparing it with direct combustion and anaerobic digestion. Gasification demonstrated the best performance in all impact categories, except for non-renewable energy use, where anaerobic digestion performed better.

Tonini et al. [63] evaluated the environmental impacts associated with heat and electricity production from one hectare of Danish land cultivated with three perennial crops: ryegrass, willow, and miscanthus. The study considered four fossil fuel conversion pathways: anaerobic co-digestion, gasification, combustion in small and medium-sized biomass CHP plants and co-firing in large coal-fired CHP plants. The scenarios of willow and miscanthus co-firing showed improvement in global warming impact compared to the reference.

Jeswani et al. [64] assessed the environmental and economic sustainability of poultry litter gasification for heat and electricity generation in the United Kingdom. Results were compared with the gasification of two other biomass feedstocks (miscanthus and waste wood) and energy from fossil fuels. Poultry litter gasification showed significant reductions in 14 out of 16 impacts compared to fossil fuels, with over 90% lower impacts than natural gas CHP, including global warming potential. Poultry litter also performed better than waste woodchips and miscanthus in most categories, except for acidification.

Mohammadi et al. [65] evaluated the cradle-to-gate life cycle impacts of energy generation from bagasse and cane trash in Iran, comparing combustion, gasification, and anaerobic digestion. The three conversion options showed different environmental outcomes, with combustion being more promising.

Parascanu et al. [66] conducted an LCA to evaluate the environmental impacts of using sugarcane and agave bagasse from Mexico for bioenergy generation. The study compared four scenarios (sugarcane/agave, combustion/gasification) from a cradle-to-gate perspective. Findings indicated high impact values in feedstock processing, with sugarcane cultivation generating 2 to 6 times more impact than agave. Thermochemical process stages had relatively low impact values, except for specific categories. Overall, agave bagasse combustion emerged as the best scenario environmentally, followed by agave bagasse gasification, sugarcane bagasse gasification, and sugarcane bagasse combustion.

Zang et al. [67] investigated the environmental performance of power-generation systems based on biomass integrated gasification combined cycle (BIGCC) through LCA. The study encompassed eight different BIGCC systems, exploring various technology options related to biomass gasification, syngas combustion, and CO_2 emission control. The key finding included that plant construction and energy efficiency influenced environmental indicators more than other parameters.

II. METHODOLOGY

The present workis primarily based on the data acquired under the collaboration with Valoriza at Politécnico de Portalegre (IPP). The data consists of biomass characteristics, the gasification process energy consumptions, and the yields and compositions of obtained products. Within retrieved data, the Ecoinvent 3 database and assumptions, the LCA and TEA have been performed.

2.1. Data collection

2.1.1. Biomassl description

The biomass feedstocks used for gasification performed by IPP were pellets of olive pomace, miscanthus and pine. First the raw biomass was dried, then milled and pelletized. Olive pomace was not milled. This feedstock does not require milling because, it comes already in small pieces after the olive oil extraction process. The exemplary photos demonstrating the different stages of the mentioned feedstocks are presented from Figure 7 to Figure 9. Meanwhile, the properties of feedstocks used for the gasification process are in Table 1.

a) Olive pomace

It is the solid waste obtained during olive oil extraction from olives. Olive pomace contains residual oil and valuable compounds, including triterpene acids and triterpene dialcohols, which exhibit antiallergic, antibacterial, antifungal, antiinflammatory, anticarcinogenic, antidiabetic, antiatherosclerotic, gastroprotective, hypolipidemic and hepatoprotective effects. The market value of olive pomace depends on its oil and water content, which rely on the olive oil extraction method (two-phase or three-phase decanter). The production of olive pomace takes place in large amounts within a short timeframe, posing challenges in management. Dry olive pomace shows potential as a source of gelling pectic material because of its polysaccharide content. Moreover, they have also been used to produce bioethanol, biogas, and methane and are the subject of research for their gasification potential [68], [69], [70]. Typically, the olive pomace lower heating value (LHV) is between 16.4 – 18.6 MJ/kg [71].

Figure 7. Biomass Feedstock at different stage: a) Olive’s cultivation; b) Dried olive pomace; c) Olive pomace pellets.

b) Miscanthus

It is a cultivated plant which can serve as an energy crop while also finding applications in the construction, pulp and paper, and automotive industries. The miscanthus can reach heights of up to 3.5 meters. It is a perennial plant, regenerating for about 20 years. It is easy to cultivate and requires less water and soil compared to other energy crops like willow or jerusalem artichoke. It gives good yields, typically averaging 20-30 tons of dry matter per hectare. Harvesting can be carried out both in autumn and spring, although it is preferred to harvest in spring for optimal energy properties due to its lower moisture and sodium content in mineral matter. Typically the miscanthus LHV should be approximately 18 MJ/kg [72], [73].

Figure 8. Biomass Feedstock at different stage: a) Miscanthus cultivation; b) Miscanthus harvested; c) Miscanthus pellets.

c) Pine

It is a widespread evergreen tree that grows well in sandy or well-drained soil, can reach heights ranging from 20 to 45 m and can live for over 400 years under optimum conditions. Pine trees are essential to many ecosystems and offer habitat and food to many species. Pine wood is widely used in the construction and paper industry. However, it is also a source of turpentine, rosin, oils, and wood tars. In addition, pine seeds are edible and commercially sold [74], [75]. Pine in the form of sawdust, woodchips or pellets is widely used as a renewable source of energy [76]. Typically, pine LHV is approximately 16 MJ/kg [77].

Figure 9. Biomass Feedstock at different stage: a) Pine trees; b) Pine woodchips; c) Pine pellets.

Table 1. Biomass feedstock characteristics – data retrieved from IPP.

Parameter	Unit	Olive pomace pellets	Miscanthus pellets	Pine pellets
Moisture content	%	9.4	6.3	7.4
Volatile Matter content	%	66.5	64.7	53.6
Fixed Carbon content	%	16.4	26.7	36.4
Ash content	%	7.7	2.3	2.6
Nitrogen content	%	1.7	0.4	0.6
Carbon content	%	53.4	44.5	49.7
Hydrogen content	%	7.5	6.1	7.5
Sulphur content	%	0.1	0	0
Oxygen content	%	20.2	40.4	32.2
Higher Heating Value (HHV)	MJ/kg	20.5	18.1	18.4
Lower Heating Value (LHV)	MJ/kg	18.5	16.3	16.4

2.1.2. Gasification process and its products

Gasification tests were carried out using two different systems: a laboratory-scale, 15 kWe downdraft fixed bed gasifier and a pilot-scale, 85 kWe bubbling fluidized bed gasifier.

The scheme of the fixed bed gasification system of IPP considered in this work is presented in Figure 10. The Fixed bed reactor has a cylindrical shape with an internal diameter of 28 cm and a height of 55 cm. The feed system consists of a feedstock storage hopper, and simultaneously, the feedstock undergoes drying through the recirculation of the syngas produced in the reactor. Biomass is transported further through a feed screw. The air is preheated by contact with the reactor walls. Ash collection is carried out at the bottom of the reactor, while the produced syngas passes through a cyclone filter to remove fine particles. The produced syngas goes through a filter, where condensate matter is removed at the bottom.

During the measurements, the controlled operational conditions included the oxidation and reduction temperatures, pressure in the reactor, airflow entering the reactor and the biomass feed rate. The operating conditions of the gasification processes in the fixed bed reactor for each biomass case presented in Table 2.

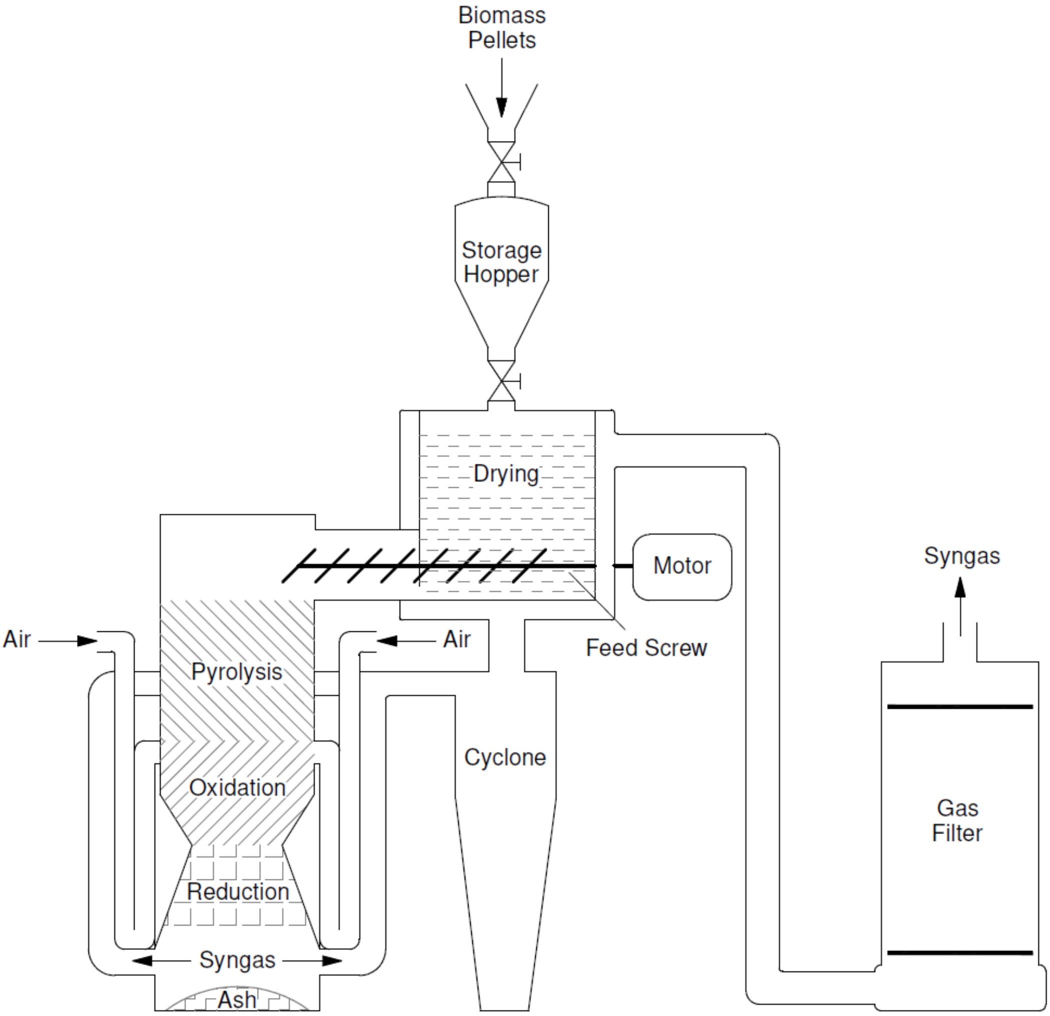

Figure 10. Scheme of fixed bed gasification system of IPP.

Table 2. Operational condition of the fixed bed gasifier.

Parameter	Unit	Olive pomace	Miscanthus	Pine
Oxidation temperature	°C	697	602	697
Reduction Temperature	°C	484	304	451
Reactor pressure	kPa	-23	-52	-21
Air flow rate	Nm^3/h	9.3	8.7	8.9
Air temperature	°C	14.9	17.3	16.6
Equivalence Ratio	-	0.32	0.42	0.35
Biomass feed rate	kg/h	5.2	5.5	5.4
Residence time	h	7	7	7

The second system considered in this work is a fluidized bed reactor, of which the scheme is presented in Figure 11. The fluidized bed reactor, has a cylindrical shape with an internal diameter of 0.5 m and a height of 4.15 m. The reactor bed consists of 36 oxidant agent inlets and a dolomite catalyst. The feeding system comprises a conveyor belt supplied by two feedstock storage hopper systems separated by valves. The produced syngas flows through the heat exchanger, which aims to lower the temperature of the syngas while simultaneously heating the air that enters the reactor. Then, it goes through a syngas cleaning system consisting of seven bag filters. The collected material falls by gravity into a container separated from the filtration system. To capture tars, a radiator with a pump responsible for circulating water in the circuit is employed, causing the condensation of tars. The tars fall by gravity and, through the pump, are transferred to the appropriate container.

Temperatures and pressure in the reactor, air flow and temperature entering the reactor, and the feed rate were all regulated operational conditions during the measurements. Table 3 shows the gasification process operating conditions of the fluidized bed gasification process of all considered biomasses.

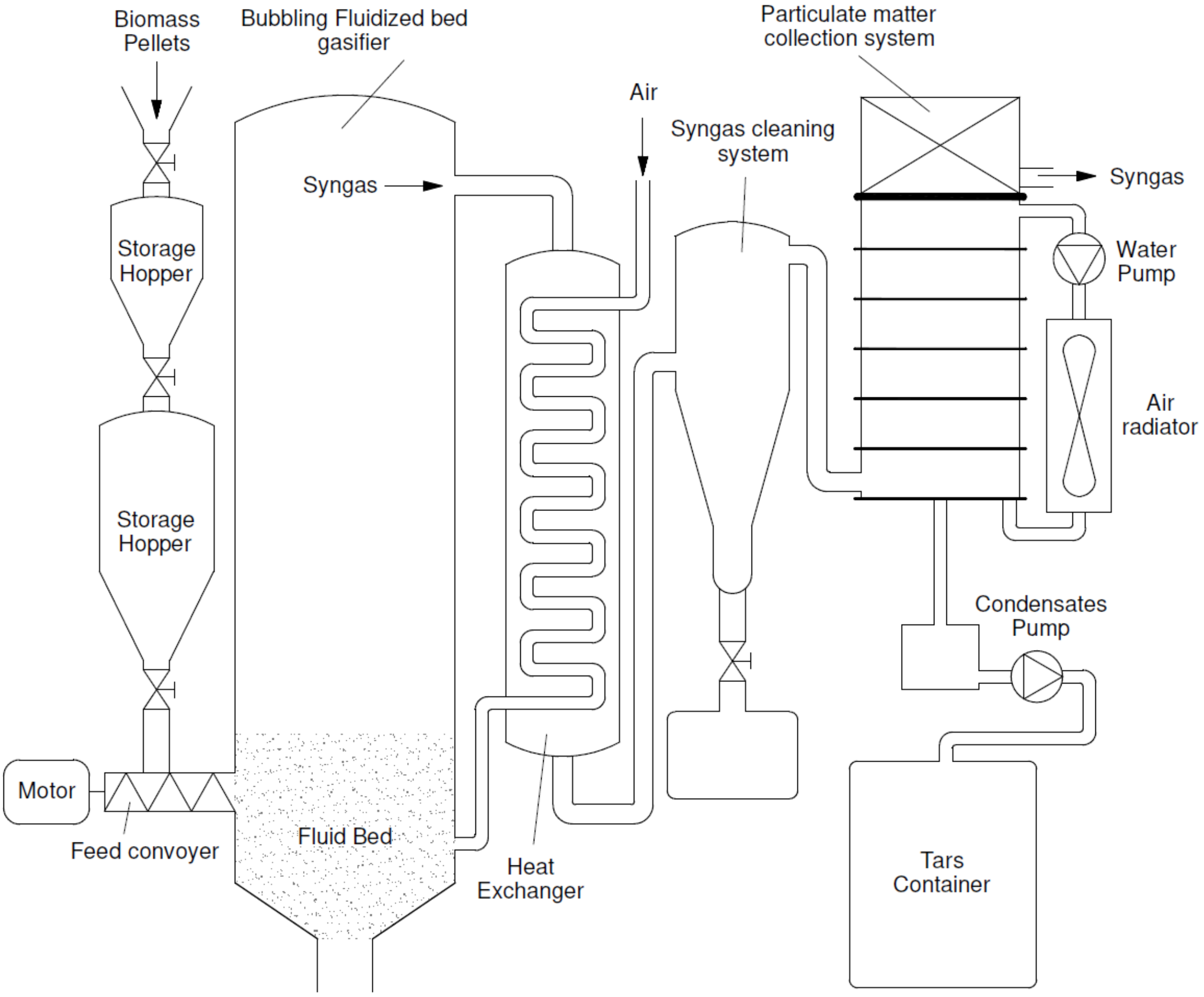

Figure 11. Scheme of fluidized bed gasification system of IPP.

Table 3. Operational condition of the fluidized bed gasifier.

Parameter	Unit	Olive pomace	Miscanthus	Pine
Temperature 1	°C	847	853	752
Temperature 2	°C	631	631	654
Temperature 3	°C	515	481	502
Reactor pressure	kPa	-48.2	-26	-38.5
Air flow rate	Nm^3/h	89.0	55.3	48.9
Air temperature	°C	95	110	95
Equivalence Ratio	-	0.27	0.27	0.19
Biomass feed rate	kg/h	55	60	60
Residence time	h	7	7	7

The syngas samples were collected in polypropylene bags when the gasification process had stabilized. Due to feed rate differences in each case, the data of gasification results was normalized by IPP to a feed rate of 100 kg/h, which allows for a comparison between the systems. The results of gasification are presented in Table 4.

Table 4. Results of analysed biomass gasification (normalized to feed rate of 100kg/h).

Parameter	Unit	Fixed bed			Fluidized bed		
		Olive pomace	Miscanthus	Pine	Olive pomace	Miscanthus	Pine
CO_2	%	8.52	11.59	11.52	16.21	15.70	17.20
C_2H_4	%	0.47	0.57	0.73	2.76	0.30	2.87
C_2H_6	%	0.09	0.14	0.19	0.14	0.00	0.30
C_2H_2	%	0.02	0.02	0.04	0.10	0.10	0.00
H_2S	%	0.05	0.04	0.00	0.00	0.00	0.00
N_2	%	55.01	54.80	54.87	52.15	50.70	50.80
CH_4	%	2.04	2.01	3.35	4.42	3.80	4.40
CO	%	19.91	18.45	15.87	11.50	13.20	16.30
H_2	%	13.56	12.32	13.21	12.7	16.2	8.13
Syngas LHV	MJ/Nm^3	4.82	4.59	4.95	5.90	4.76	6.10
Tars flow rate	Nm^3/h	0.003	0.004	0.002	0.020	0.010	0.010
Char mass rate	kg/h	6.1	3.4	3.0	4.9	3.7	5.3
Syngas flow rate	Nm^3/h	282.4	249.8	264.7	230.3	172.5	150.2
Cold Gas Efficiency (CGE)	%	73.6	70.3	80.1	73.3	50.3	56.0

Looking at the gasification results, one can notice the lower Cold Gas Efficiency (CGE) of miscanthus and pine gasification in the fluidized bed gasifier. The person responsible for the process reported clogging issues during the gasification, directly impacting the syngas yield, which is significantly lower in these cases compared to others. In general, the Lower Heating Value (LHV) is higher in a fluidized bed reactor than in a fixed bed. However, in the case of miscanthus, the LHV is on a similar level. In the case of fluidized bed gasifiers, tar creation was much higher than in the case of fixed bed, regardless of biomass.

2.2. Life Cycle Assessment (LCA)

The LCA study was carried out according to the ISO 14040:2006 with the use of SimaPro 9.1 software, which proved to be the most chosen LCA software in the scientific world due to its robust database, user-friendly interface, advanced modelling capabilities, and compliance with international standards. These features collectively contribute to the reliability, flexibility, and comprehensiveness of the LCA methodology applied in the study.

2.2.1. Goal and scope definition

The LCA study aims to investigate and compare the environmental impact of the gasification process for power generation using biomasses of three different origins in two types of reactors (fixed bed, fluidized bed) with each other and with natural gas power plant. The mentioned origins of biomasses include:

- Agriculture: Olive pomace,
- Energetic crop: Miscanthus,
- Forest: Pine.

Functional unit and system boundary

Given the study's focus on the environmental impact of gasification for energy production, the functional unit (FU) is specified as the production of 1 MWh of electricity.

The electricity production was calculated based on Equation 2:

$$\mathrm{E_{produced}} = \frac{\mathrm{V_{syngas}} \cdot \mathrm{LHV_{syngas}} \cdot \eta_{\mathrm{T}} \cdot \eta_{\mathrm{G}}}{3.6} \cdot t \tag{2}$$

where:

- $\mathrm{E_{produced}}$ – Electricity produced [kWh]
- $\mathrm{V_{syngas}}$ – volumetric syngas flow [$\mathrm{Nm^3/h}$]
- $\mathrm{LHV_{syngas}}$ – Lower Heating Value of syngas [$\mathrm{MJ/Nm^3}$]
- η_{T} – efficiency of turbine [%] (assumed 37.2%)[78]
- η_{G} – efficiency of generator [%](assumed 98%)
- t – time [h]

The LCA carried in the study includes the following biomass supply chain:

- Cultivation,
- Harvesting,
- Pretreatment (drying, milling, pelletizing),
- Gasification,
- Power Generation.

In Figure 12, the systems boundary and process schemes for olive pomace, miscanthus, and pine cases are presented. Examining Figure 12 reveals that the system boundary excludes olive plantation and olive oil plant. This exclusion is due to olive pomace being a byproduct of the olive oil extraction process, and all associated emissions and energy usage are attributed to the olive oil extraction process. In the case of miscanthus the system boundary and processes include all aspects since miscanthus is a specially cultivated energy crop. Similarly, in the case of pine, all processes are included in the system boundary. In this case, it is assumed that the pine is cultivated and later felled in the forest. Then is processed at the sawmill, where wood chips are produced specifically for energy purposes.

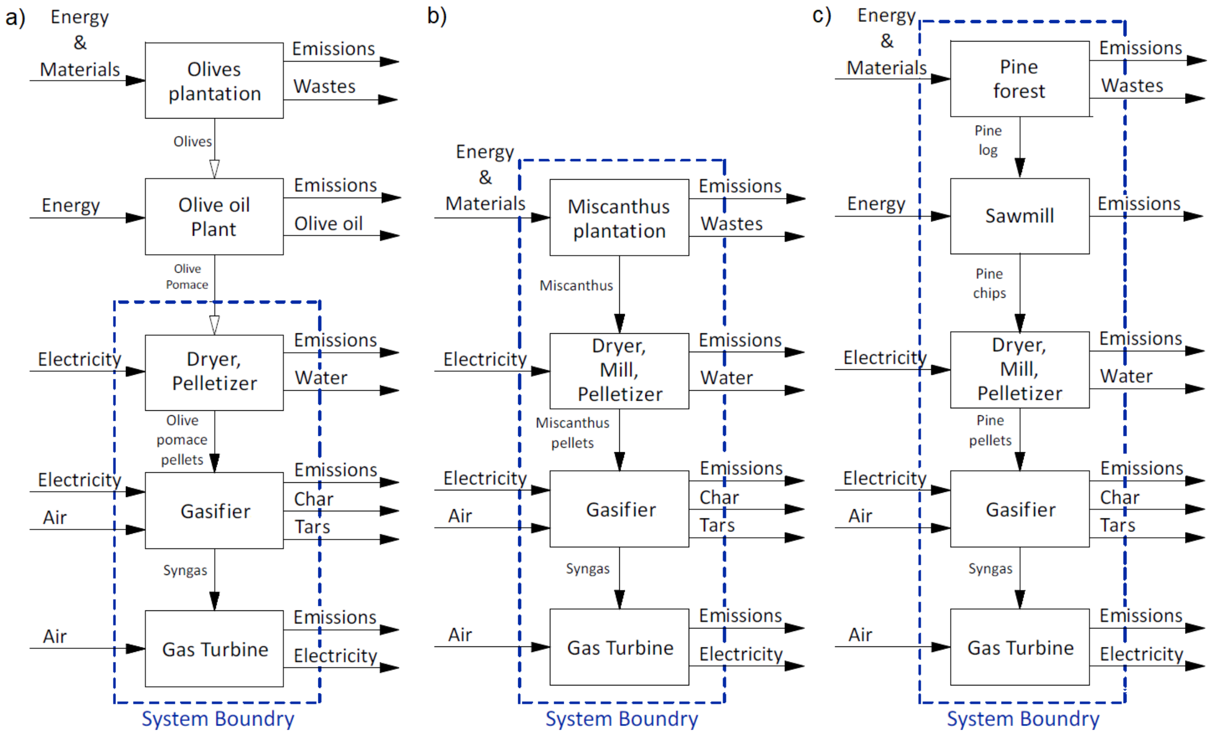

Figure 12. System boundaries and processes of feedstocks:
a) Olive pomace, b) Miscanthus, c) Pine

Assumptions and limitations

The LCA analysis is evaluated under the following assumptions:

- It is assumed that the gasification plant is in Portugal and is located at the same place as the biomass source. Therefore, biomass transportation is not taken into consideration in the analysis.
- The olive pomace is treated as byproduct from olive oil production. Therefore, the emissions and energy usage associated with cultivation and harvesting of olives were not accounted in the case of olive pomace case, since it should be associated with the production of olive oil process.
- The olive pomace obtained from the olive oil extraction process is already shredded, therefore milling in the pretreatment of biomass is not considered in the analysis for olive pomace.

2.2.2. Life Cycle Inventory (LCI)

Within the LCI phase, an inventory of input and output data for the studied system, involving necessary data collection to fulfil predefined objectives, is conducted. The primary data, such as electricity usage and feedstock amount requirements for pretreatment and gasification were retrieved from a gasification plant located at IPP, Portugal, where laboratory measurements utilizing all three specified biomasses in downdraft fixed bed and bubbling fluidized bed reactors were done. Supplementary data regarding miscanthus and pine stages of cultivation and harvesting, the emissions associated with the use of electricity (Portugal energy mix) sourced from Ecoinvent 3 - allocation, cut-off by classification database. The biogenic CO_2 emissions of combusting specific syngas of each case have been calculated based on the United States Environmental Protection Agency (EPA) Greenhouse Gas Inventory Guidance [79]:

$$\mathrm{CO_{2,emissions}} = \mathrm{V_{syngas}} \cdot \mathrm{EF_{CO2}} \cdot \frac{\mathrm{m.w._{CO2}}}{\mathrm{m.w._{C}}} \tag{3}$$

$$\mathrm{EF_{CO2}} = \sum_{i=1}^{n} \mathrm{MF_i} \cdot \mathrm{MC_{gas}} \cdot \mathrm{m.w._i} \cdot \mathrm{CF_i} \tag{4}$$

where,

- $\mathrm{EF_{CO2}}$ – $\mathrm{CO_2}$ emission factor of syngas $\left[\frac{\mathrm{kg\ C}}{\mathrm{m^3\ gas}}\right]$
- $\mathrm{MF_i}$ – molar fraction of gas component i $\left[\frac{\mathrm{kg{\cdot}mole\ i}}{\mathrm{kg{\cdot}mole\ gas}}\right]$
- $\mathrm{MC_{gas}}$ – molar concentration of gas $\left[\frac{\mathrm{kg{\cdot}mole\ gas}}{\mathrm{m^3\ gas}}\right]$
- $\mathrm{m.w._i}$ – molecular weight of gas component i $\left[\frac{\mathrm{kg\ i}}{\mathrm{kg{\cdot}mole\ i}}\right]$
- $\mathrm{CF_i}$ – carbon fraction of gas component i $\left[\frac{\mathrm{kg\ C}}{\mathrm{kg\ i}}\right]$

Table 5 and Table 6 contains the material and energy inputs, as well as the various outputs, including electricity, char, and emissions for analysed biomass feedstocks pretreatment and gasification with power generation for fixed bed and fluidized bed gasifiers.

Examining Table 5, one can notice that all inputs regarding fluidized bed miscanthus and pine cases are in much higher quantity per functional unit in comparison to the fixed bed case of those two biomasses. This is due to lower efficiency of the process, which results in higher consumption of the miscanthus and pine pellets therefore inducing additional higher requirements for example of electricity during biomass pretreatment.

When looking at Table 6, one can notice that all biomasses within fluidized bed gasification have higher amount of tar yields in compare to the fixed bed cases of the same biomasses In addition, because in the syngas composition of olive pomace and miscanthus fixed bed gasification, was H_2S, in the model have assumed SO_2 emissions.

Table 5. Inputs and outputs of biomass pretreatment models (per functional unit).

Parameter	**Unit**	**Fixed bed**			**Fluidized bed**		
		Olive pomace	**Miscanthus**	**Pine**	**Olive pomace**	**Miscanthus**	**Pine**
Input							
Feedstock$_{dry}$	kg	938	949	1163	941	1325	1662
Electricity	kWh	16	22	21	16	31	30
Output							
Feedstock (pellets)	kg	725	860	753	727	1202	1077
Emissions to air							
H_2O	kg	214	89	409	214	124	585

Table 6. Inputs and outputs of biomass gasification with power generation models (per functional unit).

Parameter	**Unit**	**Fixed bed**			**Fluidized bed**		
		Olive pomace	**Miscanthus**	**Pine**	**Olive pomace**	**Miscanthus**	**Pine**
Input							
Feedstock (pellets)	kg	725	860	753	727	1202	1077
Oxidizing agent (air)	kg	1564	1640	1499	1417	1334	1058
Electricity	kWh	112	112	116	112	185	166
Output							
Electricity	kWh	1000	1000	1000	1000	1000	1000
Char	kg	44	29	22	36	44	57
Tars	kg	25	44	21	185	156	135
Emissions to air							
$CO_{2,\ biogenic}$	kg	638	710	642	629	685	705
SO_2	kg	0.78	0.65	-	-	-	-
H_2O	kg	112	107	106	86	135	53

2.2.3. Life Cycle Impact Assessment (LCIA)

Within the LCIA, the potential environmental impacts are assessed via a set of specific environmental categories and indicators. There are two approaches (midpoint and endpoint), which complement each other with their approach to calculating the impact, and using both methods is reasonable [80]:

a) **Midpoint methods:**

Midpoint methods work on intermediate indicators, going into specific environmental impacts like emissions to air, water, or soil. These models establish links between emissions and environmental stressors but do not trace the complex chain of events leading to endpoint damage.

b) **Endpoint methods:**

These models have a direct link between environmental impacts and real damages, ranging from human health problems to biodiversity loss and resource depletion. By offering a detailed and specific analysis, the trade-off involves a higher level of uncertainty in the assessment. This method is valuable for understanding the direct consequences of human activities on specific environmental endpoints.

Midpoint method and impact categories

The chosen midpoint method is CML-IA Baseline V3.05 / EU25. CML-IA methodology is a midpoint impact assessment method proposed by scientists from CML (Center of Environmental Science of Leiden University) in 2001. EU25 means its focus on the European context (making it relevant to regional environmental conditions). This method is widely accepted and recognized [52], [60], [65], it provides a comprehensive assessment of diverse environmental impact categories [81] [82]:

- **Abiotic depletion -** This impact category addresses the resources extraction (minerals and fossil fuels). It serves as an indicator of the substance's scarcity and is expressed in kilograms of antimony equivalent (kg Sb eq).

- **Global warming -** This impact category addresses negative effects upon ecosystem, human health and material welfare and is related to greenhouse gas emissions into the atmosphere. It represents the global warming potential for a 100-year time horizon (GWP100) and is expressed in kilograms of carbon dioxide equivalent (kg CO_2 eq).

- **Ozone layer depletion (ODP) -** This impact category addresses harm to stratospheric ozone layer, leading to increased ultraviolet (UV) light reaching the Earth's surface due to ozone-depleting gases, such as CFCs, halons, and HCFCs. It describes the potential for ozone depletion of various gases in relation to the reference substance, chlorofluorocarbon-11 (CFC-11), and is expressed in kilograms of chlorofluorocarbon-11 equivalent (kg CFC11 eq).

- **Human toxicity -** This impact category addresses the human habitat and is related to the impact of toxic substances exposure through inhalation, ingestion and contact. It indicates the potential harm of a unit of chemical released into the environment and is expressed in in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq).

- **Freshwater aquatic ecotoxicity -** This impact category addresses freshwater ecosystems and is related to the emissions of toxic substances to air, water, and soil. It indicates the potential harm of a unit of chemical released into the environment and is expressed in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq).

- **Marine aquatic ecotoxicity -** This impact category addresses marine ecosystems and is related to the emissions of toxic substances to air, water, and soil. It indicates the potential harm of a unit of chemical released into the environment and is expressed in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq).

- **Terrestrial ecotoxicity -** This impact category addresses terrestrial ecosystems and is related to the emissions of toxic substances to air, water, and soil. It indicates the potential harm of a unit of chemical released into the environment and is expressed in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq).

- **Photochemical oxidation -** This impact category addresses toxic ground-level ozone formation. The photochemical oxidation is associated with emissions of carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxide (NO), ammonium, and NMVOC (non-methane volatile organic compounds) to the air and is expressed in kilograms of ethylene equivalent (kg C_2H_4 eq).

- **Acidification -** This impact category addresses negative effects on soil, groundwater, surface water, organisms, ecosystems, and buildings due to acid rain formation. It accounts emissions of SO_2, NO_x and fertilizer usage and is expressed in kilograms of sulphur dioxide equivalent (kg SO_2 eq.).

- **Eutrophication -** This impact category addresses issues of high concentrations of macronutrients in the environment due to the emission of macronutrients into the air, water, and soil, causing excessive levels of plant growth, such as algae in rivers, drastically degrading water quality and reducing animal populations. It is expressed in the reference unit of kilograms phosphate (3−) ion equivalent (kg PO4 eq).

Endpoint method and impact categories

IMPACT (MPact Assessment of Chemical Toxics) is both a midpoint and endpoint impact assessment method developed by the Swiss Federal Institute of Technology – Lausanne (EPFL) and contains the following endpoint impact categories [83]:

- **Human health -** This impact category accounts for the intensity of the disease. It considers mortality and morbidity, which are years lost to early death and years with a reduced quality of life caused by sickness. Expressed in Disability-Adjusted Life Years (DALY).

- **Ecosystem quality -** This impact category accounts for estimating the percentage of species that vanished from a square meter of earth in a single year. Expressed in Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year. Expressed in $PDF \cdot m^2 \cdot y$.

- **Climate Change –** This impact category measures amount of CO_2-eqvivalent gases released into air. Expressed in kg CO_2 eq.

- **Resources -** This impact category measures the amount of energy extracted or needed to extract the resource. Expressed in MJ.

2.3. Techno-economic analysis (TEA)

To evaluate the economic viability of gasification for olive pomace, miscanthus, and pine, a TEA has been conducted. As in the case of LCA of this study, this assessment involves the utilization of two reactors (fixed bed and fluidized bed) and is partially based on the data retrieved from IPP.

2.3.1. Data and Assumptions

The economic analysis was carried under assumption that both reactors have the same feed of 100 kg/h with operating hours of 8035h in a year (1 month off for maintenance work) in 20 years lifetime. Gasifiers are coupled with gas turbine to burn syngas on site to generate electricity. The gasification unit location is next to a facility for processing forest wood, an miscanthus plantation, or an olive oil plant processing olive in Portugal. The cost of transportation is negligible in such cases, and feedstock is available at the unit feed capacity.

Data for economic analysis has based on different literatures. The Capital Cost of Investment (CAPEX) include costs associated to various aspects, such as equipment (including the prime mover and fuel conversion system), machinery for fuel handling and preparation, engineering, and construction costs, as well as project planning.

Depending on gasifier type the price ranges differ. Lourinho et al. [84] estimated investment costs for fixed bed gasifier between 1000 - 4000 € per kW and fluidized bed gasifier between 2500 – 5000 € per kW. International Renewable Energy Agency [85] reported investment costs for fixed bed gasifier between 1610 – 4718 € per kW and fluidized bed 2300 – 4290 € per kW, whereas Cardoso et al. estimated investment costs for fluidized bed gasifier at the level of 3810 € per kW [86]. Based on this data, it assumed for the fixed bed 2500 € per kW and fluidized bed 3750 € per kW. In addition, it assumed, that investment will be realized in one year without bank loan. In the case of olive pomace price, some literature reported the price of 30 €/ton [87], [88].

Nevertheless, recent years have witnessed an oversupply of olive pomace in Portugal, resulting in challenges in its disposal [89]. These circumstances can even lead to negative prices, which is not uncommon for waste feedstocks [90]. Considering this volatility, a more conservative approach has been adopted for this study, assuming a rate of 15 €/ton of olive pomace.

In case of miscanthus price, in literature can be found ranges starting from 40 €/ton up to 134 €/ton [91], [92]. Witzel & Finger [91] have reported that prices reported in literature are either in terms of energy content or on a per-unit weight basis. The absence of data regarding the assumed moisture levels and energy content makes it challenging to make accurate comparisons. Boakye-Boaten et.al [92] noted that these prices consider various factors such as the expenses associated with collecting, processing, storing, and transporting the feedstock. This includes considerations like truck size, daily trip frequency, loading and unloading methods for containers, and the round-trip distance to be covered. Since, transportation is neglected within assumptions of the study, the price of 40€ per ton of miscanthus is considered.

In case of pine, usually literature reports prices with included transportation. This highly influence the final price. As Meyer et al. [93] and Shemfe et al. [14] reports the price of pine is at the level of 100 €/ton. However, Ferreira et al. [13] reported pine price for energy purposes for 44 €/ton, and this is the price assumed in the study as well.

Operation and maintenance costs (O&M) refer to the fixed and variable costs associated with the operation of the biomass gasification plant. Fixed O&M expenditures include labour, scheduled maintenance, regular component/equipment replacement, and insurance. Variable O&M costs consist of non-biomass fuel expenditures such as unscheduled maintenance, equipment replacement, and supplemental service fees. Fixed costs have assumed to be 4% of capital investment cost and variable costs for 0.0031 € per kWh [85]. Another cost not associated with O&M is cost of purchased electricity, which assumed to be 0.14 € per kWh [94].

In the revenues stream, electricity and biochar are sold in the gasification plant. Price of selling electricity set to be 0.113 € per kWh [86], [95], whereas the price of biochar assumed to be 0.209 €/kg [96], [97]. Additionally assumed no salvage value, no inflation, and a discount rate of 7%. All mentioned assumptions are gathered in Table 7.

Table 7. Assumptions used in economic evaluation.

Name	Unit	Value
Feedstock capacity	kg/h	100
Operating hours	h/year	8035
Lifetime	years	20
Biochar price (sell)	€/kg	0.2093
Electricity price (sell)	€/kWh	0.1132
Electricity price (buy)	€/kWh	0.1397
Feedstock price		
• Olive pomace	€/t	15
• Miscanthus	€/t	40
• Pine	€/t	44
CAPEX		
• Fixed bed	€/kW	2 500
• Fluidized bed	€/kW	3 750
OPEX		
• Variable	€/kW	0.0031
• Fixed	% of CAPEX	4
Discount rate	%	7

2.3.2. Selected economic indicators.

NPV — Net Present Value

NPV is the comparison between the discounted cash inflows and outflows, also known as cash flows, over the course of the project's lifetime. Can be expressed [98]:

$$NPV = \left(\sum_{j=1}^{n} \frac{R_j}{(1+a)^j}\right) - \left(\sum_{j=0}^{n-1} \frac{I_j}{(1+a)^j} + \sum_{j=1}^{n} \frac{c_{O\&Mj}}{(1+a)^j}\right) \tag{5}$$

where:

- n – Lifetime of project [years]
- R_j – Revenue in year j [€]
- I_j – Investment cost in year j[€]
- $c_{O\&Mj}$ – Operational & Maintencance cost in year j [€]
- a – Discount rate [%]

IRR— Internal Rate of Return

The Internal Rate of Return (IRR) is the discount rate at which the Net Present Value (NPV) of future cash flows becomes zero, therefore it is the rate at which an investment break even. The IRR was determined using the iterative Gauss method [98]:

$$IRR^{(k+1)} = \frac{R_N}{I_t}\frac{\left(1 + IRR^{(k)}\right)^n - 1}{(1 + IRR^{(k)})^n} \tag{6}$$

where:

- $R_N - \text{Annual net revenue } [€]$
- $I_t - \text{Total Investment cost } [€]$
- $k - \text{iteration's number } [-]$

DPP – Discounted Payback Period

The discounted payback is a method of calculating the number of years it will take to recover an investment after taking the discount into account [98]:

$$DPP = \frac{\ln\left(\frac{R_N}{R_N - aI_t}\right)}{\ln(1 + a)} \tag{7}$$

where:

- $R_N - \text{Annual net revenue } [€]$
- $I_t - \text{Total Investment cost } [€]$
- $a - \text{Discount rate } [\%]$

ROI – Return on Investment

Return on Investment assess actual profitability of the project as a percentage of total investment [98]:

$$ROI = \frac{\sum_{j=1}^{n} \frac{R_{Nj}}{(1 + a)^j}}{\sum_{j=0}^{n-1} \frac{I_j}{(1 + a)^j}} \tag{8}$$

where:

- $R_{Nj} - \text{Annual net revenue in year j } [€]$
- $I_j - \text{Investment cost in year j } [€]$
- $a - \text{Discount rate } [\%]$

LCOE – Levelized Cost of Energy

Levelized Cost of Energy evaluates the cost of generating electricity over the entire life cycle of a power plant. It provides a standardized way to compare the cost of electricity generation across different energy sources and technologies.

Since total investment is assumed to be at initial instant t = 0, annual utilization factor and O&M expenses are constant throughout lifetime of gasification plant the LCOE can be calculated via simplified model [98]:

$$LCOE = \frac{I_t(i + c_{O\&M})}{E_d} \tag{9}$$

$$i = \frac{1}{k_a} = \frac{a(1+a)^n}{(1+a)^n - 1} \tag{10}$$

$$E_d = \sum_{j=1}^{n} \frac{E_{aj}}{(1+a)^j} \tag{11}$$

where:

- i – Depreciation rate [%]
- E_d – Discounted Electricity Production [MWh]
- k_a – Discount factor [%]
- E_{aj} – Electricity Producton in year j [MWh]

III. RESULTS AND DISCUSSION

3.1. Life Cycle Assessment (LCA)

As stated previously in the methodology and within the study's scope, the environmental impacts associated with power generation from three distinct biomass sources, employing the two types of reactors, have been computed across eleven midpoint (Figure 13 - Figure 15) and four endpoint (Figure 16) categories where all results are normalized by expressing each value as a percentage relative to the maximum value in the set to allow a standardized comparison and representation of the data in terms of its proportion to the maximum value. Whereas the standard values of all results are presented in Table 8 for midpoint impact categories and in Table 9 for endpoint impact categories.

3.1.1. Midpoint categories comparison

The available literature on the LCA of olive pomace gasification is limited, one source being the work of Ozturk et al. [60]. It is worth noting that their study takes a different approach to the burden of olive pomace on the impacts associated with olive oil production, including olive cultivation, harvesting, olive oil extraction and olive pomace transport.

The LCA of miscanthus gasification is explored better, where Balcioglu et al. [61], Nguyen & Hermansen [62] and Jeswani et al. [64] are among the researchers. The LCA for pine gasification reveals a significant gap in the available data and literature. One literature regarding LCA of pine gasification was done by Zang et al. [67], as supporting literature used to compare waste wood data from the Jeswani et al. study [64]. All data available in the given literature was normalized to allow comparison and is presented in Table 10.

Figure 13 focuses on the first four midpoint impact categories: Abiotic depletion, Abiotic depletion (fossil fuels), Global warming (GWP 100a), and Ozone layer depletion (ODP).

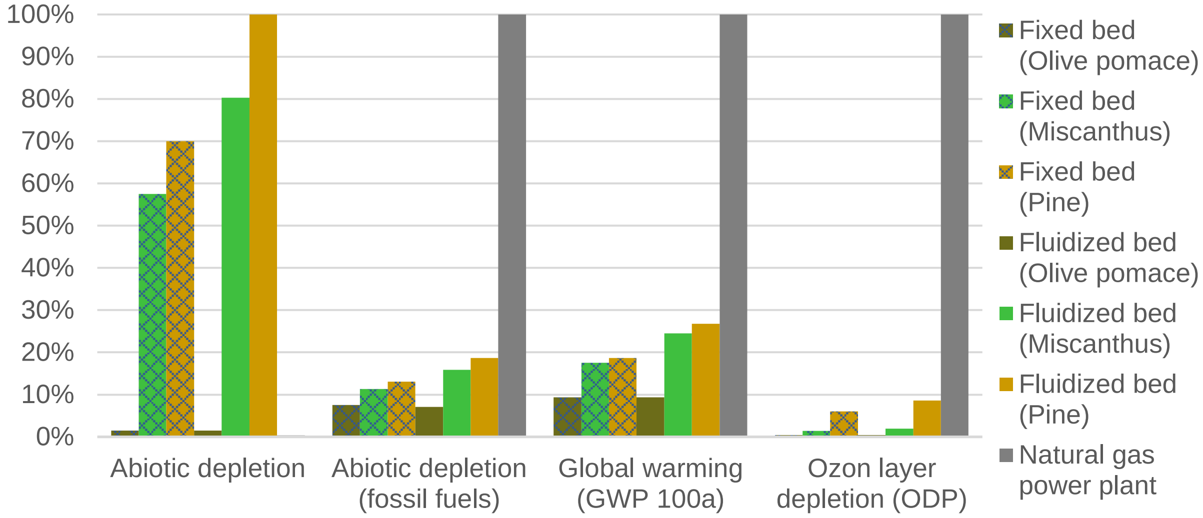

Figure 13. Comparison of midpoint impact categories: Abiotic depletion, Abiotic depletion (fossil fuels), Global warming (GWP 100a), and Ozone layer depletion (ODP).

a) Abiotic depletion

Analysing abiotic depletion in Figure 13 reveals that this category is affected the most by pine and miscanthus. Such an outcome aligns with expectations since the land is essential for cultivation. This process involves cutting indigenous flora, extracting minerals from the soil, and using fertilizers. Pine tree generally grow slower than miscanthus and that may be a reason for a higher impact on abiotic depletion.

Due to the study's assumption about olive pomace, the cultivation of olives is not included, which results in a lower impact on this category (1.5%). The natural gas power plant has little effect (0.3%) because it mainly affects abiotic depletion in terms of fossil fuels. When comparing gasifiers, in the miscanthus and pine case, the fluidized bed has a higher impact than the fixed bed by 23% and 30%, respectively. This is due to the lower efficiency of the process, leading to higher feedstock consumption. Olive pomace in both gasifiers shows a significantly lower impact at $1.2 \cdot 10^{-6}$ kg Sb eq./MWh, attributed to cultivation differences, compared to literature’s $9.5 \cdot 10^{-3}$ kg Sb eq./MWh [60]. This difference can be attributed to the cultivation stage, with land use, extraction of minerals from the soil and fertiliser application.

b) Abiotic depletion (fossil fuels)

In this category (Figure 13), the natural gas power plant stands out with the highest impact on the abiotic depletion of fossil fuels, which can be expected because natural gas is a fossil fuel which needs extraction. Other biomasses also contribute to this category due to partial reliance on fossil fuels in various moments of a life cycle, such as harvesting or utilizing electricity from the grid, which includes fossil fuel-generated power in its mix. Pine has a greater impact than miscanthus, primarily because it requires more processing, whereas olive pomace, due to the study's assumption, is the least impactful (7.5% for fixed bed and 7.1% for fluidized bed). Among gasifiers, the fluidized bed has impact higher of 4.6% and 5.6% than the fixed bed in miscanthus and pine likely due to lower process efficiency. Comparing with literature both fixed bed (860 MJ/MWh) and fluidized bed (808 MJ/MWh) olive pomace gasification show lower values but are not distinctly different from Ozturk et al.'s study of 1161 MJ/MWh [60]. For miscanthus, the study reports result of 1290 MJ/MWh for fixed bed and 1810 MJ/MWh for fluidized bed. The fixed bed value is higher but comparable to Jeswani et al. at 1151 MJ/MWh [64], and much higher than Balcioglu et al.'s 879 MJ/MWh [61]. For pine, the study reveals fixed bed and fluidized bed gasification results of 1490 MJ/MWh and 2130 MJ/MWh, notably diverging from Jeswani et al.'s findings of 868 MJ/MWh [64]

c) Global warming

In the global warming impact category (Figure 13), the analysis reveals that all biomasses have, by over 70%, lower impact than natural gas. This is strictly due to nature of feedstock. Combustion of biomass sourced fuels release so called biogenic CO_2, which in other words means that it is in a short carbon cycle and will be capture by the plants again. In contrast to fossil fuel that releases carbon that has been trapped for millions of years. Among biomasses olive pomace, regardless of the gasifier type, achieves the best result at 66 kg CO2 eq./MWh, which is 9.4% of natural gas and is lower compared to literature's 112 kg CO_2 eq./MWh [60]. Next is miscanthus and then pine from the fixed bed gasification being less harmful than natural gas by about 82.4% and 81.3%, respectively. Fluidized bed gasification due to lower process efficiency has impact higher than fixed bed for the same biomasses by 6.9% and 8.1% respectively.

Miscanthus, in fixed bed gasification, shows 124 kg CO2 eq./MWh and in fluidized bed, it is 173 kg CO2 eq./MWh. Such result falls between literature findings of 296 kg CO2 eq./MWh [62] and 110 kg CO2 eq./MWh [61],[64]. For pine, the fixed bed and fluidized bed gasification results are 132 kg CO2 eq./MWh and 189 kg CO2 eq./MWh, respectively, being close to reported value of 203 kg CO2 eq./MW [67], but much higher than waste wood (70 kg CO2 eq./MWh) [64].

d) Ozone layer depletion (ODP)

In the Ozone layer depletion (ODP) category (Figure 13), natural gas has the highest impact among the discussed cases. Such outcome can be due to the extraction and processing of natural gas that release ozone-depleting substances, depending on the sourcing. Olive pomace gasification in both fixed bed and fluidized bed cases shows values of $3.8 \cdot 10^{-7}$ kg CFC11 eq./MWh which corresponds to 0.4% of maximal impact in this category. It is also much smaller compared to $8.8 \cdot 10^{-6}$ kg CFC11 eq./MWh in literature [60][60]. For miscanthus, the study reports results of $1.2 \cdot 10^{-6}$ kg CFC11 eq./MWh and $1.7 \cdot 10^{-6}$ kg CFC11 eq./MWh for fixed bed and fluidized bed which corresponds to 1.4% and 1.9% of maximum, it also differs from literature values of $1.0 \cdot 10^{-5}$ kg CFC11 eq./MWh [61] and $1.8 \cdot 10^{-5}$ kg CFC11 eq./MWh [64]. Literature's ozone layer depletion for pine resultof $2.9 \cdot 10^{-6}$ kg CFC11 eq./MWh [67], which is lower than fixed bed ($5.4 \cdot 10^{-6}$ kg CFC11 eq./MWh) and fluidized bed ($7.7 \cdot 10^{-6}$ kg CFC11 eq./MWh) pine gasification corresponding to 6.0% and 8.6% respectively. Waste wood in Jeswani et al.'s findings has the highest value of $1.4 \cdot 10^{-5}$ kg CFC11 eq./MWh [64].

Figure 14 focuses on the next four midpoint impact categories: Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity and Terrestrial ecotoxicity.

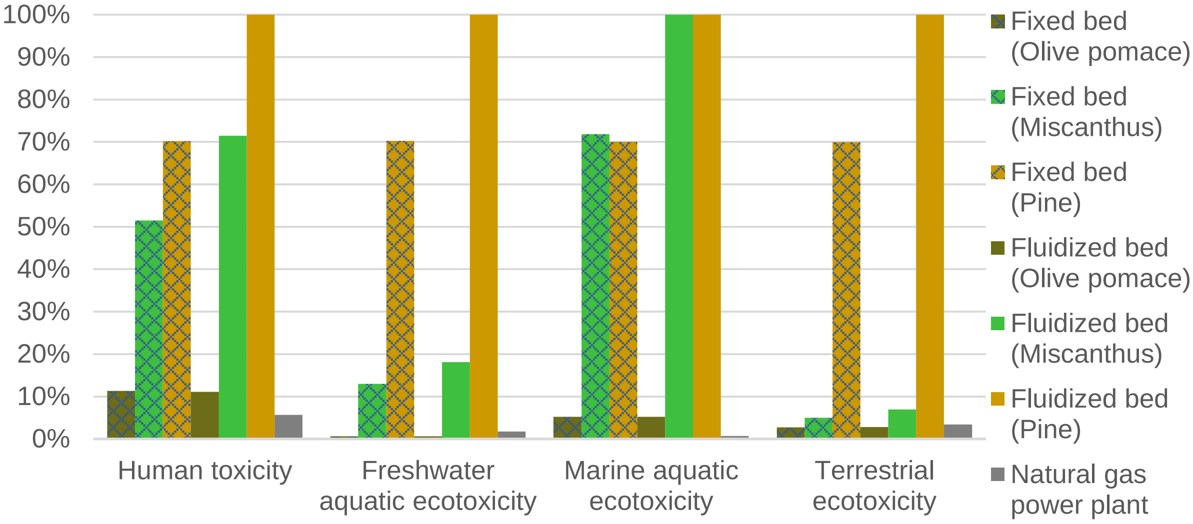

Figure 14. Comparison of midpoint impact categories: Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity.

e) Human toxicity

Analysing the human toxicity impact in Figure 14, it is possible to notice, that pine and miscanthus gasification show the greatest impact. Olive pomace and natural gas in case of human toxicity have small impact, about 11% and 6% of maximal impact in this category. The absence of the burdens of olive cultivation and harvesting in the case of olive pomace contributes to its much lower impact. The high effect of pine and miscanthus implies that those stages (cultivation and harvesting) directly impact human toxicity. Depending on the gasifier pines is about 20-30% more harmful then miscanthus in terms of human toxicity.

In terms of gasifier type, again due to efficiency of the process fixed bed has lower impact then fluidized bed. In olive pomace, literature reports 821 kg 1,4-DCB eq./MWh [60], while this study found values of 3.5 kg 1,4-DCB eq./MWh for fixed bed and 3.4 kg 1,4-DCB eq./MWh for fluidized bed. Miscanthus impacts are 15.7 kg 1,4-DCB eq./MWh for fixed bed and 21.8 kg 1,4-DCB eq./MWh for fluidized bed, with the fixed bed value similar to literature at 12.0 kg 1,4-DCB eq./MWh [64]. Balcioglu et al. reported a notably lower impact at 4.1 kg 1,4-DCB eq /MWh [61]. Pine evaluations show higher impacts, with fixed bed gasification at 21.4 kg 1,4-DCB eq./MWh and fluidized bed at 30.5 kg 1,4-DCB eq./MWh, compared to waste wood (12.3 kg 1,4-DCB eq./MWh [64]) and the lowest reported value by Zang et al. at 4.1 kg 1,4-DCB eq /MWh [67].

f) Freshwater aquatic ecotoxicity

Considering freshwater aquatic ecotoxicity in Figure 14, Pine shows the highest impact within fluidized bed and fixed bed gasification, with a difference of 30% between reactors. Miscanthus has much lesser impact (13%-18%), whereas natural gas and olive pomace have marginal impacts, being 1.7% and 0.6% respectively. Such result is again due to cultivation and harvesting stages of both pine and miscanthus. The reason why pine has a higher impact on freshwater aquatic ecotoxicity could be due to a common forestry practice of clearcutting which leads to soil disturbance and erosion [99], resulting in soil particles and chemicals or nutrients transported into rivers and streams, affecting water quality and aquatic ecosystems. Additionally, miscanthus does not require as high inputs of fertilizers and pesticides, as pine (or other crops and forestry) [100], lowering the danger of soil and groundwater contamination. In literature, olive pomace is reported to have 5.2 kg 1,4-DCB eq./MWh [60], while this study finds 0.1 kg 1,4-DCB eq./MWh for both fixed bed and fluidized bed. Miscanthus gasification results are 1.5 kg 1,4-DCB eq./MWh and 2.1 kg 1,4-DCB eq./MWh for fixed bed and fluidized bed, comparable to literature values of 1.4 kg 1,4-DCB eq./MWh [64] and 1.7 kg 1,4-DCB eq./MWh [61]. Pine gasification in this study indicates higher impacts, with fixed bed and fluidized bed at 7.9 kg 1,4-DCB eq./MWh and 11.3 kg 1,4-DCB eq./MWh, respectively, contrasting with waste wood at 1.00 kg 1,4-DCB eq./MWh [64].

g) Marine aquatic ecotoxicity

Looking at Figure 14 of marine aquatic ecotoxicity, it’s evident that pine and miscanthus show the higher percentage, while olive pomace has much less influence (5.2%) and natural gas being negligible (0.7%). However, examining Table 8, it is evident that the magnitudes of thousands kg 1,4-DCB eq./MWh impacting marine aquatic ecotoxicity are significant in all cases. As explained in previous impact categories, the fixed bed shows about a 30% lower impact or pine and miscanthus compared to the fluidized bed due to process efficiency. Ozturk et al. reported a high impact of 55079 kg 1,4-DCB eq./MWh [60] for olive pomace, while this study found 8670 kg 1,4-DCB eq./MWh for fixed bed and 8690 kg 1,4-DCB eq./MWh for fluidized bed.

For miscanthus, this study's values are significantly higher, with fixed bed gasification at 120000 kg 1,4-DCB eq./MWh and fluidized bed at 167000 kg 1,4-DCB eq./MWh, contrasting with literature values of 2.1 kg 1,4-DCB eq./MWh [64] and 2.8 kg 1,4-DCB eq./MWh [61]. Pine gasification results in significant impacts, with fixed bed and fluidized bed at 117000 kg 1,4-DCB eq./MWh and 167000 kg 1,4-DCB eq./MWh, respectively, in contrast to waste wood at 1.5 kg 1,4-DCB eq./MWh [64].

h) Terrestrial ecotoxicity

Looking at Figure 14 and analysing the terrestrial ecotoxicity impact category, similar trend to freshwater aquatic ecotoxicity can be noticed, with the most influential pine case. The impacts of miscanthus, olive pomace and natural gas are below 10% in compared to pine. The reason for such outcome is the same as freshwater aquatic ecotoxicity category, but the magnitude is much smaller if one compares the values in Table 8. For olive pomace gasification, both fixed bed and fluidized bed have results of 0.02 kg 1,4-DCB eq./MWh, contrasting with the literature value of 1.83 kg 1,4-DCB eq./MWh [60]. In miscanthus, the study's results are smaller, with 0.04 kg 1,4-DCB eq./MWh for fixed bed and 0.06 kg 1,4-DCB eq./MWh for fluidized bed, compared to literature values of 0.16 kg 1,4-DCB eq./MWh [64] and 0.21 kg 1,4-DCB eq./MWh [61]. Pine has higher impacts in the study, with fixed bed and fluidized bed pine gasification at 0.61 kg 1,4-DCB eq./MWh and 0.878 kg 1,4-DCB eq./MWh, respectively, while literature values for waste wood are 0.15 kg 1,4-DCB eq./MWh [64].

Figure 15 focuses on the last three midpoint impact categories: Photochemical oxidation, Acidification and Eutrophication.

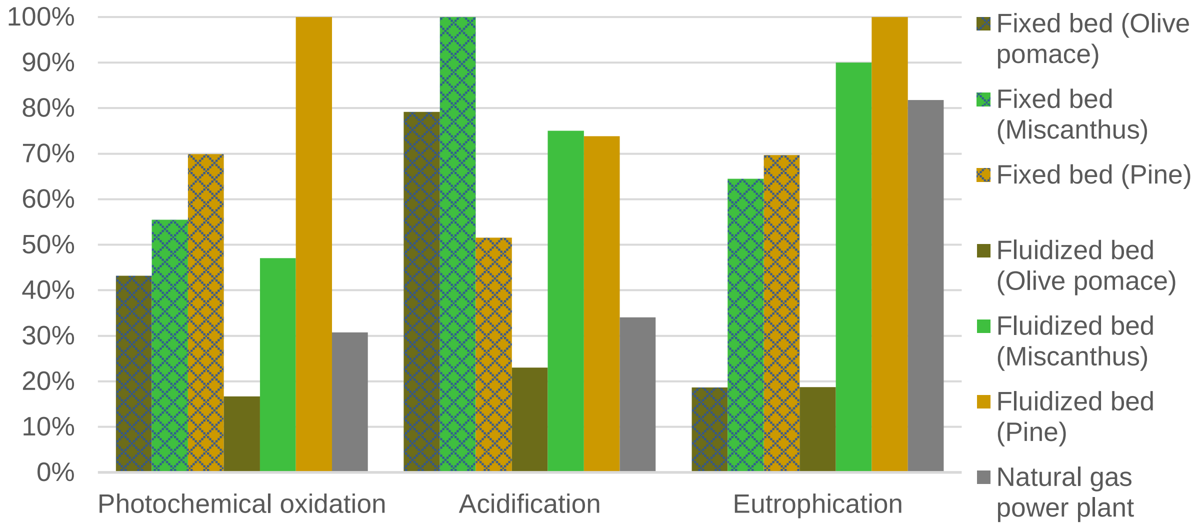

Figure 15. Comparison of midpoint impact categories: Photochemical oxidation, Acidification, Eutrophication.

i) Photochemical oxidation

Examining photochemical oxidation impact category at Figure 15, it is evident that pine contributes more to this impact category. The reason for it can be due to utilization of fertilizers, machinery, and other processes during cultivation and harvesting leading to release of NO_x into the atmosphere, which is the primary compound responsible for photochemical oxidation. Unlike in previous impact categories, fixed bed gasification of miscanthus and olive pomace have higher impacts then fluidized bed by about 8.5% and 26.5%, respectively. The reason may be due to the presence of H_2S in the syngas produced during the gasification process. Upon combustion, H_2S leads to the release of SO_2, which contributes to photochemical oxidation and acidification. Due to lack of H_2S in syngas composition of fluidized bed olive pomace gasification, has the lowest impact of 16.7%, whereas natural gas place itself on second least harmful in this category (30.8%). For olive pomace, fixed bed gasification is higher at 0.06 kg C_2H_4 eq./MWh compared to literature's 0.04 kg C_2H_4 eq./MWh [60], while fluidized bed gasification is lower at 0.02 kg C_2H_4 eq./MWh

j) Acidification

Examining the acidification impact category (Figure 15) reveals that cases with the presence of H_2S in the syngas have highest impact. The fixed bed gasification of miscanthus and olive pomace contributes significantly to acidification, primarily due to the presence of H_2S in the syngas, leading to the release of SO_2 during combustion. The lowest impact has fluidized bed olive pomace gasification (23.0%), and second is natural gas (34.0%). Even though fluidized bed pine and miscanthus did not had H_2S in syngas, these have higher impact due to low efficiency process. For olive pomace gasification, the fixed bed has 1.33 kg SO_2 eq./MWh, slightly higher than the reported 1.29 kg SO_2 eq./MWh [60]. On the other hand, fluidized bed olive pomace gasification has a smaller impact of 0.39 kg SO_2 eq./MWh. Comparing the results of miscanthus align with the literature, fixed bed at 1.68 kg SO_2 eq./MWh and fluidized bed at 1.26 kg SO_2 eq./MWh, compared to 1.05 kg SO_2 eq./MWh [61] and 1.60 kg SO_2 eq./MWh [62]. For pine, fixed bed and fluidized bed are over twice as high, 0.87 kg SO_2 eq./MWh and 1.24 kg SO_2 eq./MWh, respectively, compared to literature 0.42 kg SO_2 eq./MWh [67].

k) Eutrophication

In the case of eutrophication (Figure 15), regardless of the reactor, olive pomace gasification has the lowest impact of 18.7%, compared to the highest impact of fluidized bed pine. The next most harmful are fluidized bed miscanthus gasification (90.0%), along with natural gas power plants (81.8%). However, fixed bed gasification of those biomasses has a lower impact than natural gas power plant by about 17% and 12% for miscanthus and pine respectively. For olive pomace, fixed bed, and fluidized bed gasification exhibit values of 0.02 kg PO_4 eq./MWh each, compared to the higher 0.624 kg PO_4 eq./MWh [60]. Miscanthus has 0.08 kg PO_4 eq./MWh and 0.11 kg PO_4 eq./MWh for fixed bed and fluidized bed, respectively, compared to literature reports of 7.8 kg PO_4 eq./MWh [64]. Pine, in fixed bed and fluidized bed, has higher impacts (0.08 kg PO_4 eq./MWh and 0.12 kg PO_4 eq./MWh, respectively) than literature values of 0.03 kg PO_4 eq./MWh [67].

The obtained results for olive pomace, miscanthus and pine align to the literature in some impact categories, while in others there are considerable differences. The limited availability of literature prevents an in-depth analysis. On top of that, many factors on the way may influence the results, such as assumptions, the gasification process, the composition of obtained syngas, and the energy mix of the county.

3.1.2. Endpoint categories comparison

Analysis of the midpoint impact categories has identified patterns and some insights into the environmental impacts of different biomass gasification processes. In this chapter discussed are specific endpoint impact categories, covering human health, ecosystem quality, climate change and resource depletion (Figure 16).

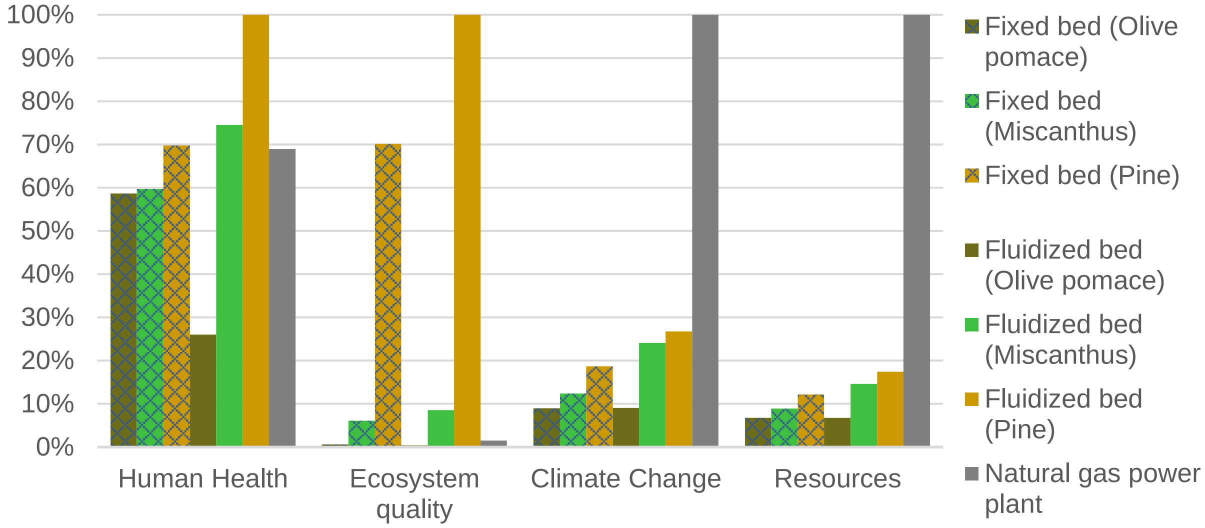

Figure 16. Comparison of endpoint impact categories.

a) Human Health

When it comes to comparing impact on human health (Figure 16), is noticed that it is mostly affected by fluidized bed pine gasification. A lot of pine processing depending on fossil fuels, higher amounts of fertilizers and pesticides and low efficiency of the gasification process contributes to higher NO_x emissions. For the same reason, but due to lower usage of fertilizers and pesticides, fluidized bed gasification of miscanthus is second more harmful, within the context of human health impact category. Followed by fixed bed pine and natural gas, almost identical, with the difference of 0.84%. Such results are probably due to higher NO_x emissions, which are primary substances responsible for photochemical oxidation responsible for the formation of pollutants causing respiratory and health problems on humans [101]. Olive pomace gasification in fluidized bed has the lowest impact (26.0%) due to lack of H_2S content in syngas composition in contrast to fixed bed miscanthus and olive pomace. The SO_2 severely effects the human respiratory, cardiovascular, and nervous systems [102].

b) Ecosystem quality

Examining ecosystem quality depicted in Figure 16, pine stands out the most as the most harmful regardless of the used gasifier. The difference between reactors is about 30% (due to process efficiency difference), but even higher when compare pine with other biomasses.

The reason for such an outcome can be due to land changes, which may contribute to disruptions in local ecosystems. Cutting out trees, destroys natural habitats, and leads to biodiversity loss and impact ecosystems. Pesticides usage to protect pine trees affects insects and birds [103] and may influence other animals. It is similar case with miscanthus, but the damage is much lower compared to pine as it was also shown within freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity midpoint categories. In comparison to pine and miscanthus, the olive pomace seems to have negligible effect on the ecosystem, which is reasonable considering that it is a byproduct of olive oil production, so does not involve land-use changes. Additionally natural gas has about 0.9% higher impact than olive pomace.

a) Climate change

When examining the climate change impact category in Figure 16, the observed pattern closely resembles that of the midpoint global warming category. All biomasses due to carbon sequestration have a much lower impact than natural gas. Olive pomace has the smallest impact of about 9.0%, compared to natural gas, regarding the gasifier. However, dependency on fixed bed or fluidized bed gasification influences miscanthus and pine gasification cases. Both biomasses have less impact in a fixed bed than in a fluidized bed due to the efficiency of the cold gas in the process carried out.

d) Resources

Regarding resources, the natural gas power plant certainly has the highest influence on resource depletion (Figure 16). Given that natural gas is a non-renewable fossil resource that needs extraction, this was an expected outcome. The biomasses also rely on fossils during a life cycle, therefore the next most impactful are fluidized bed pine (17.4%) and miscanthus (14.7%) gasification due to the low process efficiency. The lowest impact in this category has olive pomace, with a result of about 6.8% regardless of the reactor.

In summary, the least environmentally damaging option is fluidized bed gasification of olive pomace. Notably, it's crucial to highlight that within olive pomace gasification, the fluidized bed method is less harmful compared to the fixed bed approach, potentially only due to the H_2S content and SO_2 emission. This underscores the significance of employing effective gas cleaning and treatment techniques in gasification systems to mitigate the presence of sulphur compounds and minimize associated environmental impacts. From the environmental point of view utilization of pine is not considered to be ecological solution in compared to other analysed biomasses, due to its high impact on ecosystems quality. The usage of miscanthus demonstrates a more environmentally friendly choice. Moreover, in most midpoint and all endpoint categories, fixed bed miscanthus and pine gasification was found to be less harmful than fluidised bed gasification due to the low efficiency This demonstrates that increasing efficiency is important for clean solutions, but also proves that gasification is a complex process that is challenging in operating the process. On the other hand, natural gas has shown a compromise between high impacts on resources and climate change, but low impact on ecosystems quality, with similar level of impact on human health as other biomasses.

Table 8. LCA results of midpoint impact categories in reference to functional unit.

Impact Category	**Unit**	**Fixed bed**			**Fluidized bed**			**Natural gas power plant**
		Olive pomace	**Miscanthus**	**Pine**	**Olive pomace**	**Miscanthus**	**Pine**	
Abiotic depletion	kg Sb eq.	$1.17 \cdot 10^{-6}$	$4.56 \cdot 10^{-5}$	$5.55 \cdot 10^{-5}$	$1.17 \cdot 10^{-6}$	$6.37 \cdot 10^{-5}$	$7.93 \cdot 10^{-5}$	$2.70 \cdot 10^{-7}$
Abiotic depletion (fossil fuels)	MJ	860	1 290	1 490	808	1 810	2 130	11 400
Global warming (GWP 100a)	kg CO_2 eq.	66.1	124	132	66.3	173	189	706
Ozon layer depletion (ODP)	kg CFC11 eq.	$3.79 \cdot 10^{-7}$	$1.24 \cdot 10^{-6}$	$5.38 \cdot 10^{-6}$	$3.80 \cdot 10^{-7}$	$1.73 \cdot 10^{-6}$	$7.69 \cdot 10^{-6}$	$8.93 \cdot 10^{-5}$
Human toxicity	kg 1,4-DCB eq.	3.5	15.7	21.4	3.39	21.8	30.5	1.74
Freshwater aquatic ecotoxicity	kg 1,4-DCB eq.	0.07	1.47	7.94	0.07	2.05	11.3	0.19
Marine aquatic ecotoxicity	kg 1,4-DCB eq.	8 670	120 000	117 000	8 690	167 000	167 000	1 190
Terrestrial ecotoxicity	kg 1,4-DCB eq.	0.02	0.04	0.06	0.02	0.06	0.88	0.03
Photochemical oxidation	kg C_2H_4 eq.	0.06	0.08	0.10	0.02	0.07	0.14	0.04
Acidification	kg SO_2 eq.	1.33	1.68	0.87	0.39	1.26	1.24	0.57
Eutrophication	kg PO_4 eq.	0.02	0.08	0.08	0.02	0.11	0.12	0.10

Table 9. LCA results of endpoint impact categories in reference to functional unit.

Impact Category	Unit	Fixed bed			Fluidized bed			Natural gas power plant
		Olive pomace	Miscanthus	Pine	Olive pomace	Miscanthus	Pine	
Human Health	DALY	$7.69 \cdot 10^{-5}$	$7.82 \cdot 10^{-5}$	$9.14 \cdot 10^{-5}$	$3.41 \cdot 10^{-5}$	$9.76 \cdot 10^{-5}$	$1.31 \cdot 10^{-4}$	$9.03 \cdot 10^{-5}$
Ecosystem quality	$PDF \cdot m^2 \cdot yr$	2.52	25.2	291	1.71	35.6	415	6.4
Climate Change	kg CO_2 eq.	61.3	84.3	127	61.5	164	182	680
Resources	MJ primary	857	1 130	1 550	860	1 860	2 210	12 700

Table 10. LCA literature data of midpoint impact categories in reference to 1 MWh.

Impact Category	Unit	Olive pomace [60]	Miscanthus [61],[62],[64]	Pine [64],[67]
Abiotic depletion	kg Sb eq.	$9.5 \cdot 10^{-3}$	-	-
Abiotic depletion (fossil fuels)	MJ	1161	879 - 1151	868
Global warming (GWP 100a)	kg CO_2 eq.	112	110 - 296	70 - 203
Ozon layer depletion (ODP)	kg CFC11 eq.	$8.8 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$ - $1.8 \cdot 10^{-5}$	$2.9 \cdot 10^{-6}$ - $1.4 \cdot 10^{-5}$
Human toxicity	kg 1,4-DCB eq.	821	4.1 - 12.0	4.1 - 12.3
Fresh water aquatic ecotox.	kg 1,4-DCB eq.	5.2	1.4 - 1.7	1.0
Marine aquatic ecotoxicity	kg 1,4-DCB eq.	55079	2.1 - 2.8	1.5
Terrestrial ecotoxicity	kg 1,4-DCB eq.	1.83	0.15 - 0.21	0.15
Photochemical oxidation	kg C_2H_4 eq.	0.04	-	-
Acidification	kg SO_2 eq.	1.29	1.05 - 1.60	0.42
Eutrophication	kg PO_4 eq.	0.62	7.8	0.03

3.2. Techno-economic Analysis (TEA)

As mentioned within the methodology, this section provides the results of key economic indicators to show the economics of the studied biomass gasification processes. The Net Present Value (NPV) distribution across 20 years lifetime of the projects has been presented from Figure 17 to Figure 22.

Figure 17 presents the Net Present Value (NPV) of gasifying olive pomace in a fixed bed reactor, reaching 507 864 € over a 20-year period, resulting in a substantial Return on Investment (ROI) of 2.47. Achieving a Discounted Payback Period (DPP) within 5 years and 3 months demonstrates the economic viability of the investment, attributed to the combination of inexpensive feedstock and high gasification efficiency. Moreover, the Internal Rate of Return (IRR) for the project, set at a robust 23%, surpasses the chosen discount rate of 7%. This not only signifies a high level of project profitability but also indicates that the venture remains financially viable even under a more conservative discounting scenario.

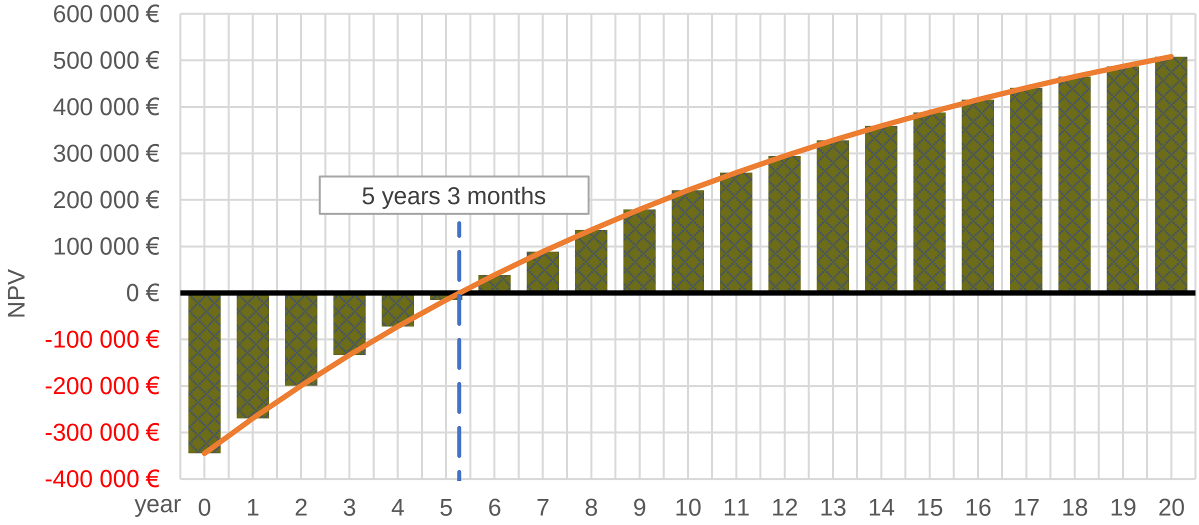

Figure 17. NPV of olive pomace gasification in fixed bed reactor.

The NPV for miscanthus gasification in the fixed bed reactor (Figure 18) over a 20-year project timeline amounts to 43 595 €, resulting in a Return on Investment (ROI) of 1.15. Moreover, the Discounted Payback Period (DPP) is extended to 15 years and 4 months, and the Internal Rate of Return (IRR) is 9%, indicating a less lucrative scenario compared with the olive pomace fixed bed gasification case. Reduced profitability and higher risk can be attributed to a combination of factors, including a higher feedstock price and lower process efficiency, leading to higher operating costs and reduced revenues.

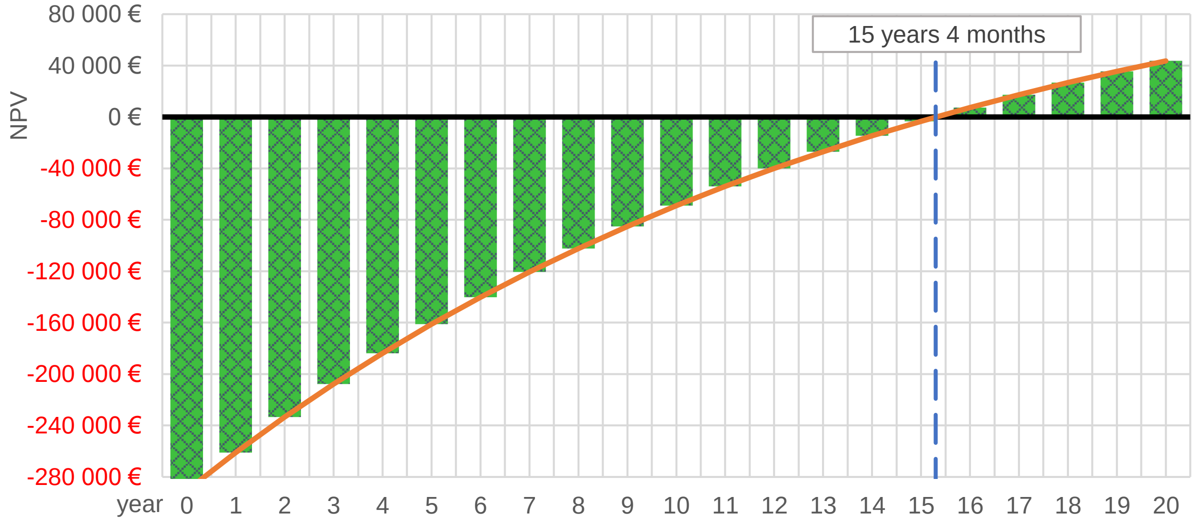

Figure 18. NPV of miscanthus gasification in fixed bed reactor

The Net Present Value (NPV) of pine gasification in the fixed bed reactor (Figure 19) amounts to 89 729 € after a 20-year project lifespan. This outcome has a Discounted Payback Period (DPP) of 12 years and 11 months and a return on investment (ROI) of 1.27. With an Internal Rate of Return (IRR) of 10%, the project's overall profitability remains positive, under study assumptions. Despite pine's highest feedstock price, the enhanced gasification efficiency positions this case as more profitable than the miscanthus fixed bed case. However, it remains considerably less compelling than the olive pomace fixed bed case.

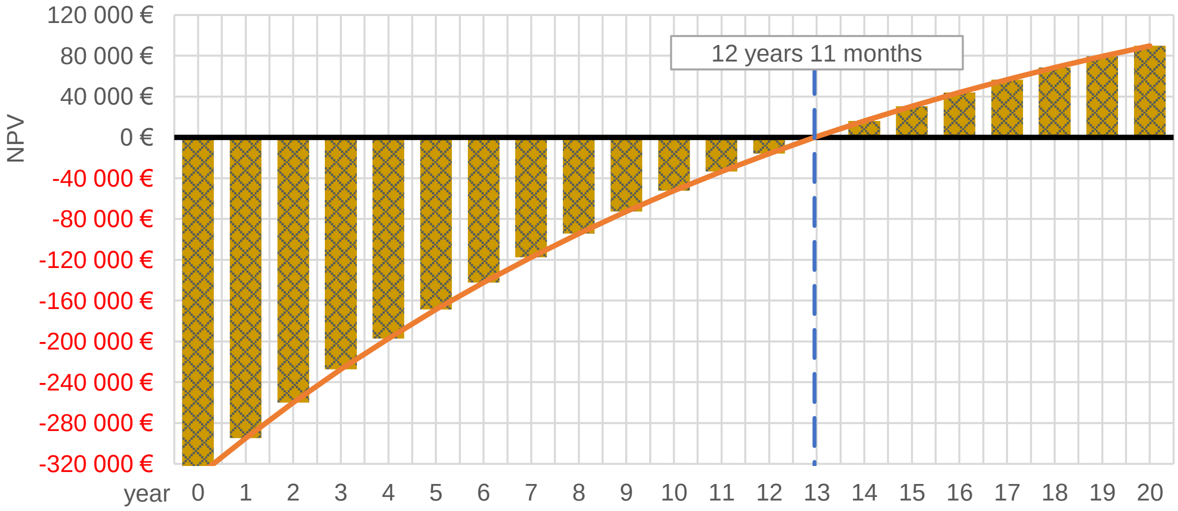

Figure 19. NPV of pine gasification in fixed bed reactor

The economic outlook of the fluidized bed gasifier cases is less favourable as opposed to the fixed bed reactor for the same biomasses. Over a 20-year project duration, the NPV for fluidized bed olive pomace gasification (Figure 20) accumulates to 240 445 €, resulting in a Return on Investment (ROI) of 1.47. The Discounted Payback Period (DPP) is achieved within 10 years and 5 months. The Internal Rate of Return (IRR) at 12% provides a comprehensive financial perspective, indicating the project's viability and attractiveness under more conservative discount rates.

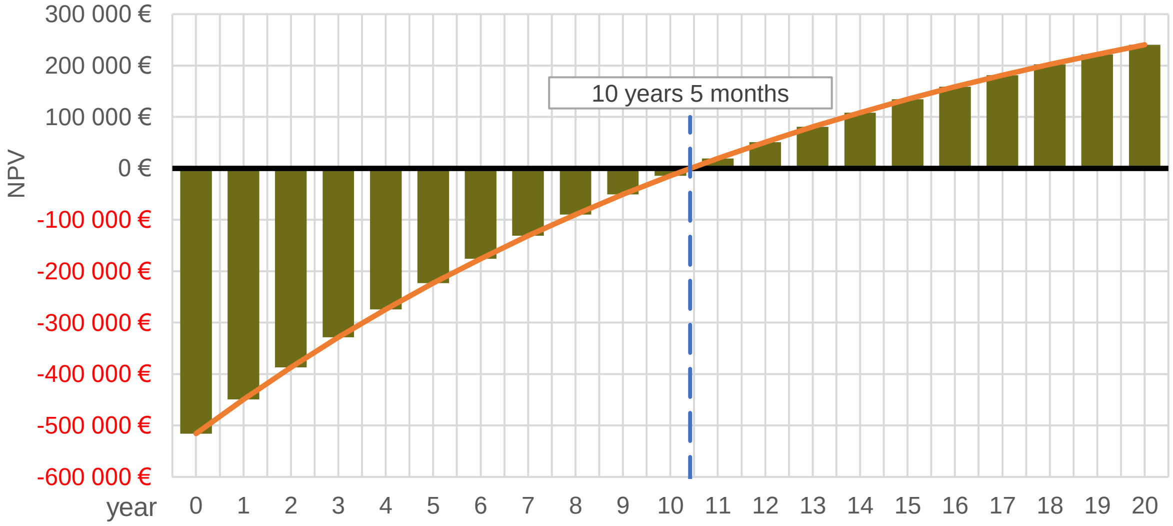

Figure 20. NPV of olive pomace gasification in fluidized bed reactor

In the context of miscanthus gasification in a fluidised bed gasifier (Figure 21), the project is economically not feasible. The Net Present Value (NPV) after 20 years is -285 089 €. Such an outcome is primarily due to low gasification efficiency (50.3%). This inefficiency significantly increases operating and raw material costs, leaving insufficient revenue to cover the expenditure.

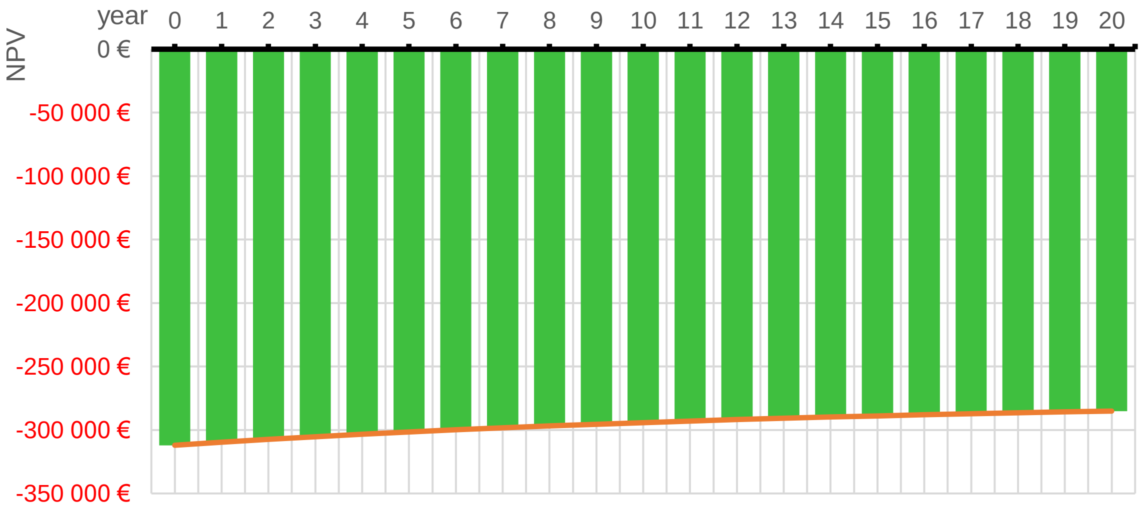

Figure 21. NPV of miscanthus gasification in fluidized bed reactor

A similar outcome is observed in pine gasification in a fluidized bed (Figure 22). The NPV after 20 years is -257 530 €, marginally better than the miscanthus case, yet still indicating economic infeasibility. Once more, the principal factor contributing to this result is the low efficiency (56.0%) of the carried gasification process.

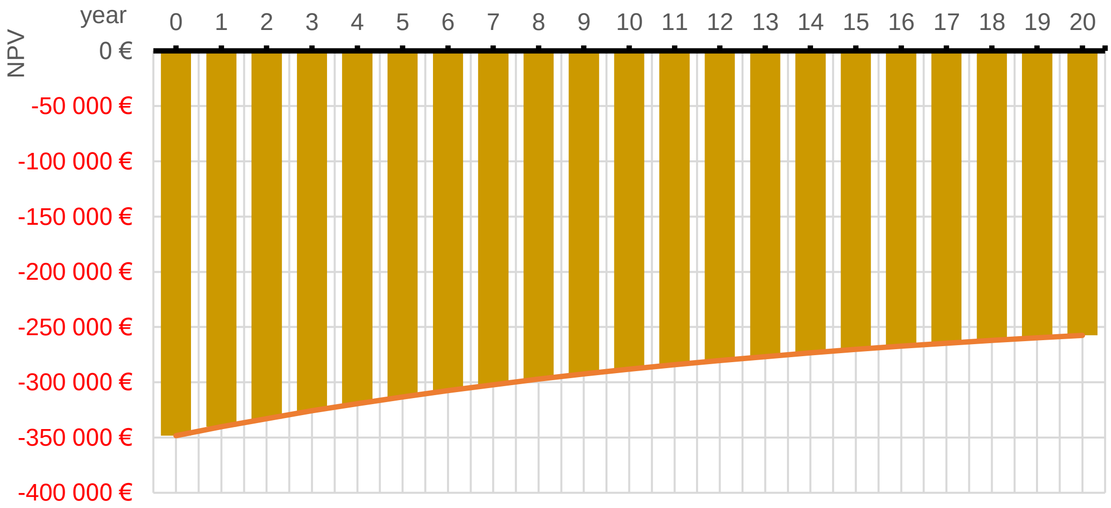

Figure 22. NPV of pine gasification in fluidized bed reactor

The Levelized Cost of Energy (LCOE) is the lowest in the case of olive pomace gasification, which is 41.5 €/MWh and 52.9 €/MWh for fixed bed and fluidised bed, respectively. Next is the gasification of pine and then miscanthus in a fixed bed with results of 58.2 €/MWh and 60.9 €/MWh, respectively. The most expensive is the gasification of pine and miscanthus in a fluidised bed, with LCOE results at 84.0 €/MWh and 86.7 €/MWh, respectively.

These LCOE results align within the LCOE range of biomass (Figure 23) based on the database compiled by Timilsin & Govind [104]. Fixed bed olive pomace is slightly below the range (-5.0%) and fluidized bed place at the lower end of the range (+1.7%). Fixed bed pine and miscanthus are 4.7% and 6.6% above the lowest reported value, whereas fluidized bed gasification of those biomasses place at 20.6% and 22.4% within the range. However, the LCOE data include power generation through various technologies for biomass power generation and consists of different capacity factors, feedstocks, CAPEX and OPEX.

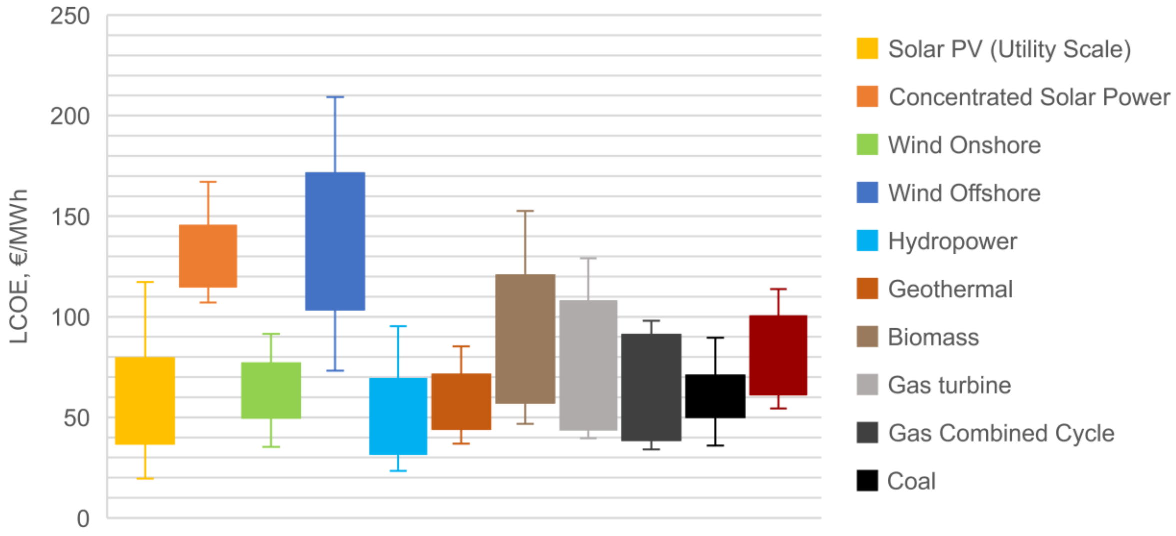

Figure 23. Levelized Cost of Energy (LCOE) of different power generation solutions. Based on 2020 database at discount rate of 7% [104].

When comparing the LCOE results with other technologies (Figure 23), it is noticed that utility-scale PV panels are currently the most cost-effective technology. Other renewables, except Concentrated Solar Power (CSP) and Wind Offshore, have LCOE lower than bioenergy (in most cases). Nevertheless, they are not dispatchable due to strong dependence on weather conditions, but the development of energy storage technology could mitigate it. However, it would influence the overall LCOE of those systems, and the difference with biomass technologies would decrease significantly. In comparison to fossil fuels, bioenergy is also usually more expensive.

The obtained results also align with the 2021 IRENA report, which claimed that projects utilizing inexpensive feedstocks like agricultural or forestry residues, as well as wastes from the processing of agricultural or forestry products found at industrial processing facilities, tend to have the lowest Levelized Cost of Energy (LCOE) [105], which is proven by the case of olive pomace.

The results of TEA are presented in Table 11.

Table 11. TEA results of the analysed biomasses for fixed bed and fluidized bed gasifiers

Economic indicator	Unit	Fixed bed			Fluidized bed		
		Olive Pomace	Miscanthus	Pine	Olive Pomace	Miscanthus	Pine
$NPV_{20\ years}$	€	507 864	43 595	89 729	240 445	-285 089	-257 530
IRR	%	23	9	10	12	0	0
DPP	years	5.27	15.30	12.95	10.42	-	-
ROI	-	2.47	1.15	1.27	1.47	0.09	0.26
LCOE	€/MWh	41.5	60.9	58.2	52.9	86.7	84.0

Overall olive pomace is the most economically viable biomass feedstock. Usage of fixed bed gasifier gives better results than fluidised bed gasifier. Even though the yields for olive pomace were at a similar level for both gasification, the fluidised bed gasifier is more expensive. In addition, the cases of fluidised bed gasification of miscanthus and pine show economic infeasibility, characterised by negative NPVs after 20 years. This outcome proves the importance of process efficiency, as low efficiency contributes to higher operating and feedstock costs, outweighing potential revenues. However, it is crucial to incorporate uncertainty into economic assessments, accounting variables such as feedstock prices, operating costs, and market fluctuations. Sensitivity analysis investigates these uncertainties, examining how essential parameter changes affect the economic viability the projects.

3.2.1. Sensitivity Analysis

As the data and assumptions used within the economic analysis have a direct impact on the results, the Sensitivity Analysis covers price changes within +/- 30% of the originally assumed prices and is presented on Figure 24 to Figure 30. In the context of olive pomace gasification in a fixed bed gasifier, the selling price of electricity significantly influences the NPV after 20 years (Figure 24). Then, CAPEX is the second most significant, followed by feedstock price, fixed and variable costs, and buying electricity price. Biochar sell price is the least impactful. The NPV after 20 years is always positive in this framework.

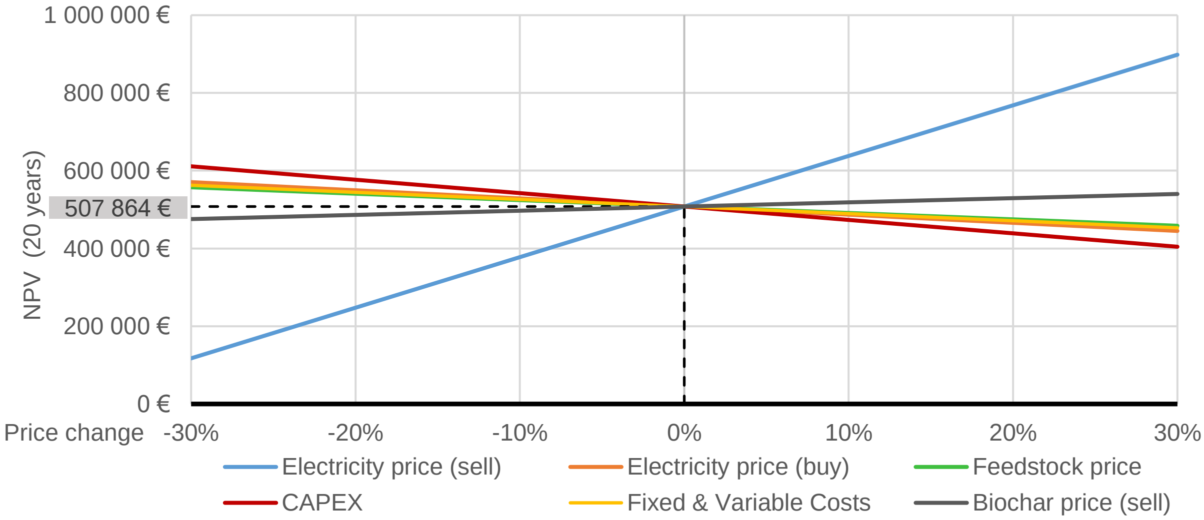

Figure 24. Sensitivity analysis of olive pomace gasification in fixed bed reactor

Analysing sensitivity analysis for fixed bed miscanthus gasification (Figure 25), it is at a sensitive point in terms of profitability. Decreasing the electricity sell price by -10% or increasing the feedstock price by +10% would lead to a negative Net Present Value (NPV) after 20 years. Capital Expenditure (CAPEX), electricity purchase price, and the combined fixed and variable costs, if increased by +30%, would also end with negative NPV. Due to low biochar yields, the selling price of biochar has minimal impact on NPV.

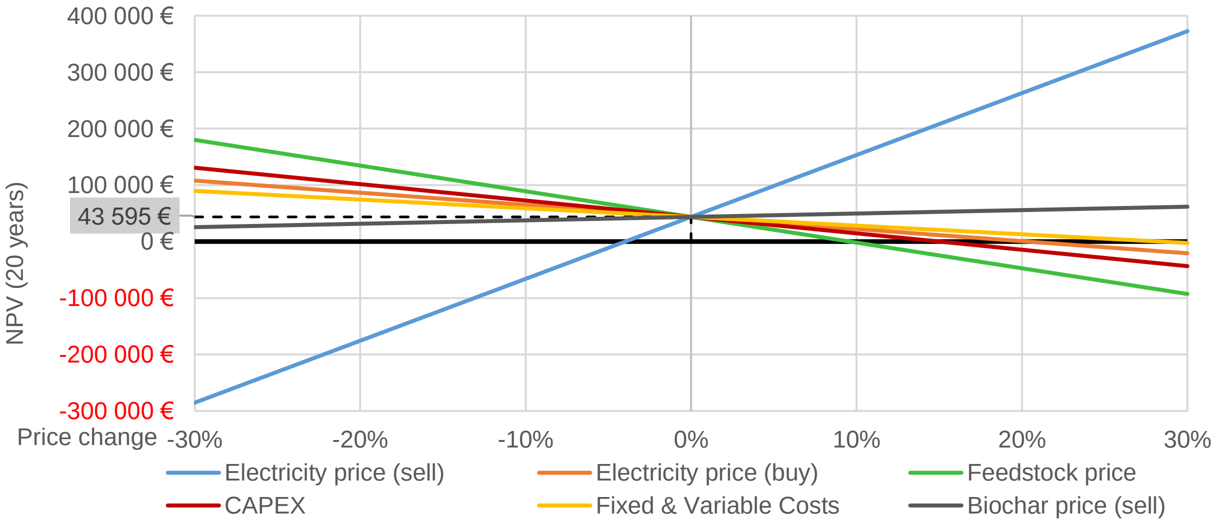

Figure 25. Sensitivity analysis of miscanthus gasification in fixed bed reactor

Similarly, to miscanthus fixed bed case, the gasification of pine in a fixed bed gasifier (Figure 26), decreasing the electricity sell price by -10% or increasing the feedstock price by +20% or Capital Expenditure (CAPEX) by +30% would lead to a negative Net Present Value (NPV). Biochar sell price has almost no effect on NPV.

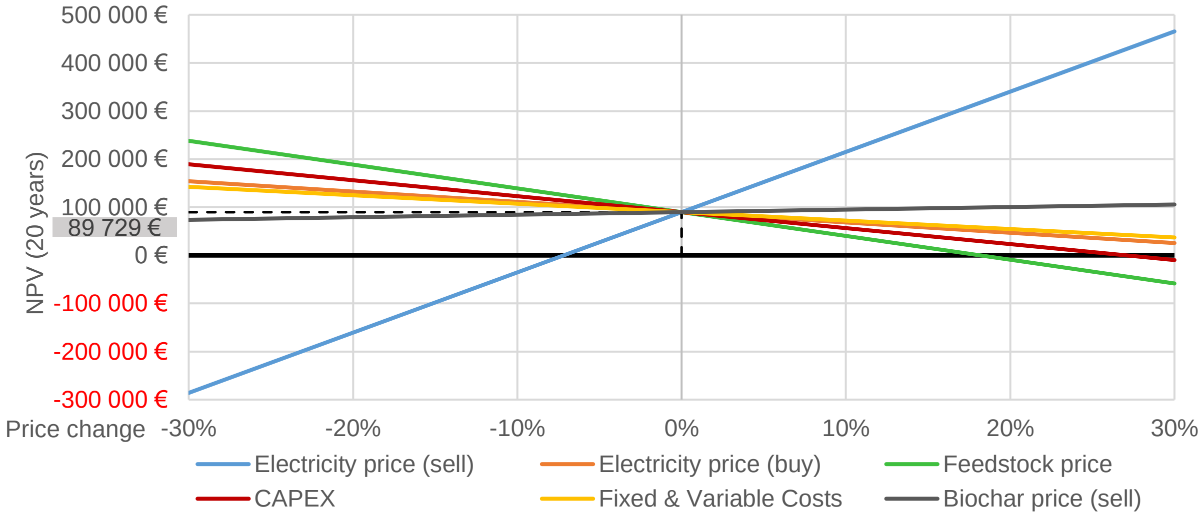

Figure 26. Sensitivity analysis of pine gasification in fixed bed reactor

When considering the sensitivity analysis of olive pomace gasification in a fluidized bed (Figure 27), similarities to the fixed bed case are noticed. The difference is that if the electricity sales price dropped by -20%, the project would not be profitable, whereas in the fixed bed case, it is still profitable even with a 30% price drop.

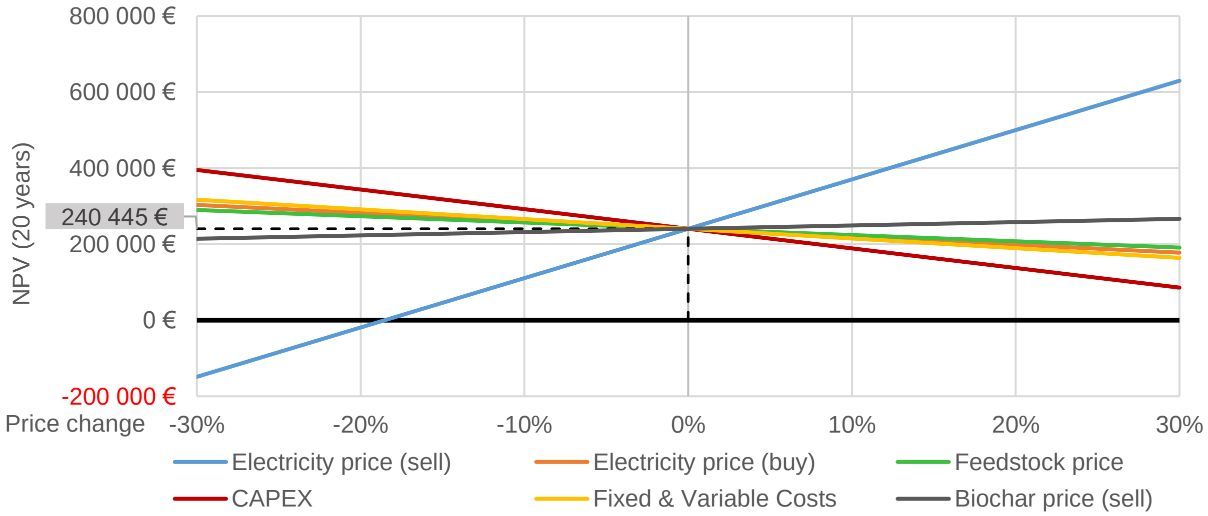

Figure 27. Sensitivity analysis of olive pomace gasification in fluidized bed reactor

In sensitivity analysis cases of fluidized bed gasification of miscanthus (Figure 28), like in other cases, the most influential factor is electricity sell price followed by feedstock price, with the least impacting biochar sell price. However, any price change within +/- 30% framework does not make the project profitable. The electricity sales price would have to exceed +37% (Figure 29) to break through an NPV equal to 0 after 20 years.

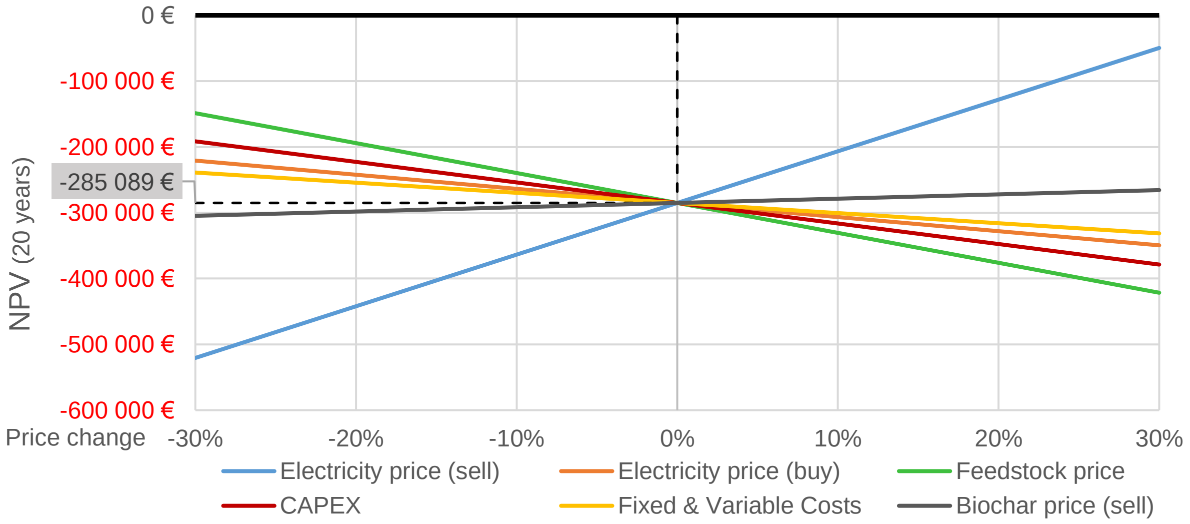

Figure 28. Sensitivity analysis of miscanthus gasification in fluidized bed reactor

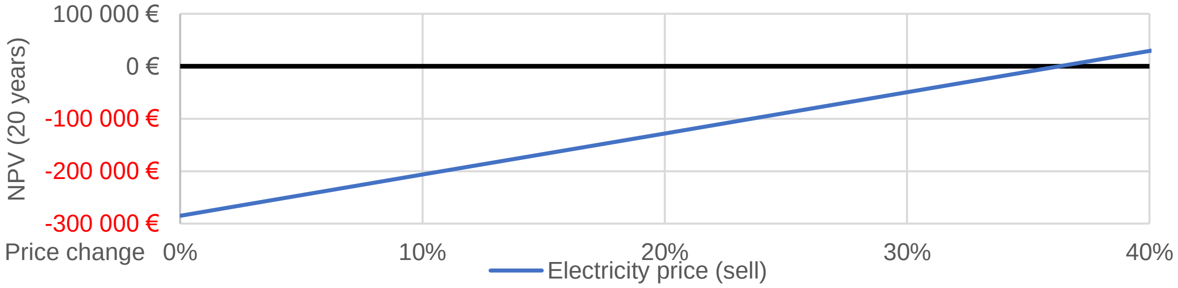

Figure 29. Electricity price change to achieve a positive NPV (fluidized bed miscanthus gasification)

In the case of fluidized bed gasification of pine (Figure 30), like in other cases, the most influential is the electricity sell price, followed by the feedstock price, with the least impacting biochar sell price. A +30% increase in the selling price of electricity would result in break-even after 20 years, while changes in other prices within the assumed range would not make the project profitable.

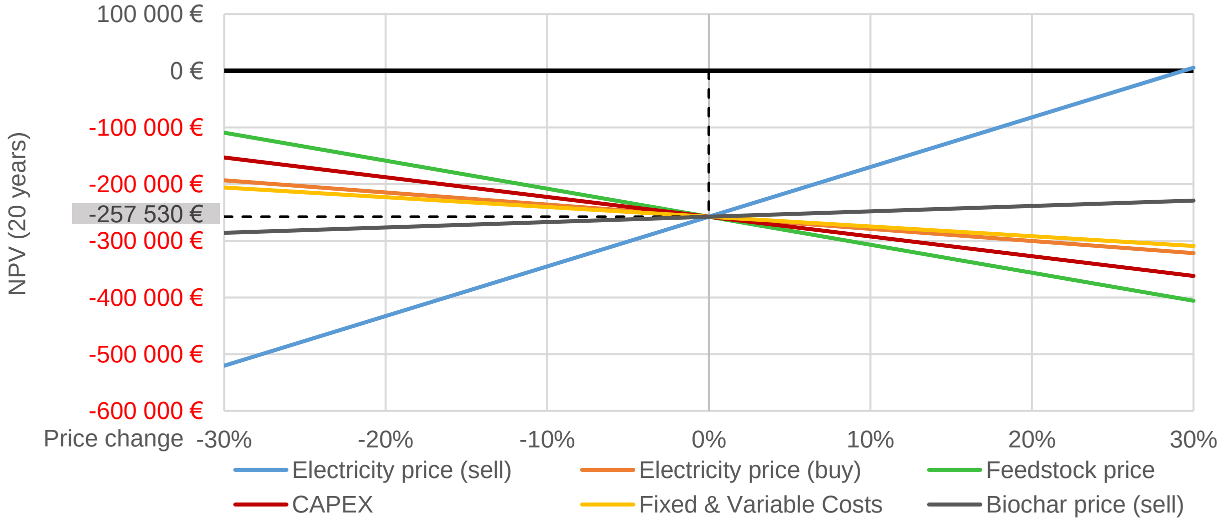

Figure 30. Sensitivity analysis of pine gasification in fluidized bed reactor

3.2.2. Technical challenges of biomass gasification

Economic analysis has shown that biomass gasification can be economically attractive, despite the economic potential, the path to widespread large-scale adoption presents challenges across commercial, legislative, and technological aspects.

Feedstock supply and handling challenges:

A crucial factor dictating the success of biomass-based projects is the availability of biomass. Larger power plants, requiring a substantial biomass source, face the challenge of its potential unavailability or substitution with other, sometimes more expensive feedstock [105]. The unpredictability with biomass, unlike fossil fuels, raises investor caution. Biomass properties, including different presence of minerals, varying O_2 content and low bulk density, affect plant and gasification efficiency [106]. Low bulk density creates distribution and logistics challenges [107] but also creates the need for greater size and more expensive handling equipment, which can result in regulatory restrictions. Because of the lower biomass density, more pressurization gases are needed to maintain a constant flow, raising operating costs and increasing greenhouse gas emissions [108].

Technological and operating process challenges:

Maintaining the optimal operating temperature is critical for efficient thermochemical conversion. However, achieving precise temperature control becomes difficult due to fluctuations in feedstock properties and surrounding factors [109]. The handling of high temperatures and pressures demands strict safety procedures and operator training to ensure unit’s safe operation [110]. Tar produced during biomass gasification, when condensed, pose both technical and financial challenges [111]. Researchers actively explore methods to mitigate tar formation, including the use of various catalysts and agents to enhance gas quality and reduce tar levels [112]. Electrochemical reforming has emerged as a promising approach, specifically targeting lighter tar compounds [51]. The syngas resulting from biomass gasification may contain ultrafine particles, known as soot, which can obstruct ducts and compromise process efficiency. Effectively controlling soot levels is essential for both commercialization and process stability. It has been investigated that soot reduction can be done by torrefying and leaching the raw biomass [113]. Furthermore, studies indicate that using porous particles in fluidised bed gasifiers can lead to soot-free synthesis gas [114]. All these factors combined interfere with the overall stability of gasifier operation above 500 kW [115].

Institutional and market challenges:

Uncertain biomass prices impact electricity generation tariffs, creating investment risks that obstruct the development of gasification technologies with investors being reluctance toward large-scale gas technology adoption [116]. Approved manufacturers of biomass gas generators remain limited, with many barriers including regulatory constraints, limited access to biomass feedstocks, significant initial investment requirements, compliance with pollution standards, licensing policies, and strict product testing for market survival [46]. From a commercial point of view, the main barriers are high-risk investment and limited revenue generation [117] as it was also proved within economic assessment of this study, where the revenue was mainly due to electricity sold, and as sensitivity analysis has shown the electricity price decided about successful of the project.

IV. CONCLUSIONS

Due to the escalating harmful effects of climate change driven by, among others, greenhouse gas (GHG) emissions of fossil-based electricity production, more environmentally friendly alternatives are being explored. This study assesses the environmental impact and economic feasibility with technical challenges through an LCA and TEA of the gasification process of different biomass feedstocks and utilization of produced syngas for power generation based on experimental data.

The study found that olive pomace is the most ecologically friendly biomass among all considered cases and the most economically attractive, with relatively quick returns and lower risk. In comparison, pine and miscanthus include a trade-off. Pine gasification has the highest environmental impact among studied biomasses, especially within ecosystem quality, about 11 times more than miscanthus, but its economics is twice better than miscanthus within a fixed bed, whereas in the case of a fluidised bed, both biomasses are not economical. However, olive pomace depends on seasonality and the feedstock availability may raise concerns. In addition, olive pomace seems a solid choice of biomass feedstock in Portugal's case and should prove itself in regions with olive oil production. However, in countries without olive plantations, other agricultural waste biomass should be considered. The Levelized Cost of Energy (LCOE) has shown that energy production from other renewable energy sources is usually less expensive, especially solar PV systems. Nevertheless, these systems are weather-dependent, so diversification of energy sources is necessary as part of the phase-out of fossil fuels.

Gasification technology faces many challenges influencing the development of this solution on a large scale, one of them being proper operation conditions. There is a notable difference in results between the laboratory-scale (fixed bed) and pilot-scale (fluidized bed), resulting in generally better results for fixed bed than fluidized bed gasification, strengthening the statement that challenges rise as the scale increases. This study also highlighted the significance of gasification process efficiency by demonstrating that low efficiency builds up issues, such as higher costs and emissions, along with lower revenue streams. Additionally, the study underlined the importance of proper gas cleaning, proving that syngas containing hydrogen sulphide in their composition led to more environmental damage. It is worth keeping in mind that usually, the laboratory environment does not fully reflect reality, and the environmental and economic assessment used assumptions. On top of that, the world is very dynamic with fluctuating markets. In trying to foresee those factors, a sensitivity analysis revealed that electricity price changes significantly influence the potential of project success.

Overall, olive pomace gasification is a promising ecologically friendly technology for generating electricity, which can contribute to phasing out fossil fuels while also being waste treatment, contributing to decreasing the waste stream problem created during olive oil production. On the other hand, in countries where olives are not grown, miscanthus can be an environmentally friendly option, but economics is something to look at and find ways to improve. Gasification of pine showed high impact on ecosystem quality, and other alternatives should be considered.

While some of the results of this study align with existing research, the insufficient exploration of the topic in the scientific community suggests a need for further studies, specifically focusing on olive pomace gasification on a large scale to understand its full potential. While olive pomace is a promising feedstock, future research should also include biomass from other agricultural wastes in regions without olive plantations. It is needed to address the challenges of seasonal and regional feedstock availability, which are crucial as a steady supply of low-cost agricultural residues increases capacity factors while maintaining positive economic performance since insufficient quantities on a large scale may lead to greater reliance on supplementing more expensive feedstocks, which can compromise economic outcomes. Moreover, assessing the viability of different feedstocks and their availability can contribute to a more diverse and resilient bioenergy landscape. Furthermore, given the challenges observed in gasification technology, future work should continue to explore the optimisation of operating conditions for higher efficiencies and gas purification processes.

REFERENCES

[1] Hu, Y., Zhang, Q., Hu, S., Xiao, G., Chen, X., Wang, J., Qi, Y., Zhang, L., & Han, L. (2022). Research progress and prospects of ecosystem carbon sequestration under climate change (1992–2022). Ecological Indicators, 145, 109656. https://doi.org/10.1016/j.ecolind.2022.109656

[2] Dhakal, C., Khadka, S., Park, C., & Escalante, C. L. (2022). Climate change adaptation and its impacts on farm income and downside risk exposure. Resources, Environment and Sustainability, 10. https://doi.org/10.1016/j.resenv.2022.100082

[3] Stoler, J., Brewis, A., Kangmennang, J., Keough, S. B., Pearson, A. L., Rosinger, A. Y., Stauber, C., & Stevenson, E. G. (2021). Connecting the dots between climate change, household water insecurity, and migration. In Current Opinion in Environmental Sustainability (Vol. 51, pp. 36–41). Elsevier B.V. https://doi.org/10.1016/j.cosust.2021.02.008

[4] Institute for Economics & Peace. Over one billion people at threat of being displaced by 2050 due to environmental change, conflict and civil unrest. 2020.

[5] Lee, J., & Yang, J. S. (2019). Global energy transitions and political systems. Renewable and Sustainable Energy Reviews, 115. https://doi.org/10.1016/j.rser.2019.109370

[6] Merzic, A., Turkovic, N., Ikanovic, N., Lapandic, E., Kazagic, A., & Music, M. (2022). Towards just transition of coal regions - Cultivation of short rotation copies and dedicated energy crops for biomass co-firing vs photo voltaic power plants. Energy Conversion and Management: X, 15. https://doi.org/10.1016/j.ecmx.2022.100267

[7] Acaru, S. F., Abdullah, R., Lai, D. T. C., & Lim, R. C. (2022). Hydrothermal biomass processing for green energy transition: insights derived from principal component analysis of international patents. Heliyon, 8(9). https://doi.org/10.1016/j.heliyon.2022.e10738

[8] Tezer, Ö., Karabağ, N., Öngen, A., Çolpan, C. Ö., & Ayol, A. (2022). Biomass gasification for sustainable energy production: A review. International Journal of Hydrogen Energy, 47(34), 15419–15433. https://doi.org/10.1016/j.ijhydene.2022.02.158

[9] IRENA (2022), World Energy Transitions Outlook 2022: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi. Available

[10] Basu P., 2013. Biomass Gasification, Pyrolysis and Torrefaction Practical Design and Theory. USA: Elsevier. ISBN: 978-0-12-396488-5.

[11] Chen, W. H., Lin, B. J., Huang, M. Y., & Chang, J. S. (2015). Thermochemical conversion of microalgal biomass into biofuels: A review. In Bioresource Technology (Vol. 184, pp. 314–327). Elsevier Ltd. https://doi.org/10.1016/j.biortech.2014.11.050

[12] Mahmud, Roksana & Moni, Sheikh & High, Karen & Carbajales-Dale, Michael. (2021). Integration of techno-economic analysis and life cycle assessment for sustainable process design – A review. Journal of Cleaner Production. 317. https://doi.org/10.1016/j.jclepro.2021.128247

[13] José Ferreira, Dennis Jones, Bruno Esteves, Luisa Cruz-Lopes, Helena Pereira & Idalina Domingos (2021) Life Cycle Assessment of Maritime Pine Wood: A Portuguese Case Study, Journal of Sustainable Forestry, 40:5, 431-445, https://doi.org/10.1080/10549811.2020.1768871

[14] Shemfe, M., Gu, S., & Fidalgo, B. (2017). Techno-economic analysis of biofuel production via bio-oil zeolite upgrading: An evaluation of two catalyst regeneration systems. https://doi.org/10.1016/j.biombioe.2017.01.020

[15] Sadh, P. K., Duhan, S., & Duhan, J. S. (2018). Agro-industrial wastes and their utilization using solid state fermentation: a review. Bioresources and Bioprocessing, 5(1), 1. https://doi.org/10.1186/s40643-017-0187-z

[16] Honorato-Salazar, J. A., & Sadhukhan, J. (2020). Annual biomass variation of agriculture crops and forestry residues, and seasonality of crop residues for energy production in Mexico. Food and Bioproducts Processing, 119, 1–19. https:/doi.org/10.1016/j.fbp.2019.10.005

[17] United States. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Bioenergy Technologies Office, “Biomass Resources”. Available online: https://www.energy.gov/eere/bioenergy/biomass-resources Accessed: 23.09.2023.

[18] Zafar S., (2023). BioEnergy Consult, Biomass as Renewable Energy Resource. Available online: https://www.bioenergyconsult.com/biomass-resources/ Accessed: 23.09.2023.

[19] Breeze, P. (2018). Chapter 4 - Waste to Energy Technologies. In P. Breeze (Ed.), Energy from Waste (pp. 29–37). Academic Press. https://doi.org/10.1016/B978-0-08-101042-6.00004-2

[20] European Commission, Sewage sludge. European Commission - Environment. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/sewage-sludge_en Accessed: 23.09.2023.

[21] European Commission. (2021). Energy Crops. Knowledge for Policy. Available online: https://knowledge4policy.ec.europa.eu/glossary-item/energy-crops_en Accessed: 23.09.2023.

[22] European Commission (2020). Algae biomass production for the bioeconomy. Available online: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/algae-biomass-production-bioeconomy-2020-01-17_en Accessed: 23.09.2023.

[23] Bajpai, P. (2020). Biomass conversion processes. In Biomass to Energy Conversion Technologies (pp. 41–151). https://doi.org/10.1016/B978-0-12-818400-4.00005-0

[24] Chen, H., & Wang, L. (2016). Technologies for Biochemical Conversion of Biomass. In Technologies for Biochemical Conversion of Biomass.

[25] Sawatdeenarunat, C., Surendra, K. C., Takara, D., Oechsner, H., & Khanal, S. K. (2015). Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities. Bioresource Technology, 178, 178–186. https://doi.org/10.1016/j.biortech.2014.09.103

[26] Papale, M.; Romano, I.; Finore, I.; Lo Giudice, A.; Piccolo, A.; Cangemi, S.; Di Meo, V.; Nicolaus, B.; Poli, A. Prokaryotic Diversity of the Composting Thermophilic Phase: The Case of Ground Coffee Compost. Microorganisms 2021, 9, 218. https://doi.org/10.3390/microorganisms9020218

[27] Chandel, A. K., Garlapati, V. K., Singh, A. K., Antunes, F. A. F., & da Silva, S. S. (2018). The path forward for lignocellulose biorefineries: Bottlenecks, solutions, and perspective on commercialization. Bioresource Technology, 264, 370–381. https://doi.org/10.1016/j.biortech.2018.06.004

[28] Chandraratne, M. R., & Daful, A. G. (2021). Recent Advances in Thermochemical Conversion of Biomass. In M. Bartoli & M. Giorcelli (Eds.), Recent Perspectives in Pyrolysis Research (p. Ch. 8). IntechOpen. https://doi.org/10.5772/intechopen.100060

[29] Garba, A. (2020). Biomass Conversion Technologies for Bioenergy Generation: An Introduction. In T. P. Basso, T. O. Basso, & L. C. Basso (Eds.), Biotechnological Applications of Biomass (p. Ch. 1). IntechOpen. https://doi.org/10.5772/intechopen.93669

[30] Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable and Sustainable Energy Reviews, 55, 467–481. https://doi.org/10.1016/j.rser.2015.10.122

[31] Kan, T., Strezov, V., & Evans, T. J. (2016). Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. Renewable and Sustainable Energy Reviews, 57, 1126–1140. https://doi.org/10.1016/j.rser.2015.12.185

[32] Roy, P., & Dias, G. (2017). Prospects for pyrolysis technologies in the bioenergy sector: A review. Renewable and Sustainable Energy Reviews, 77, 59–69. https://doi.org/10.1016/j.rser.2017.03.136

[33] Santanu, D., Avinash, K.A., Moholkar, V.S., Thallada, B. (2018) Coal and Biomass Gasification. Recent Advances and Future Challenges. Springer Nature Singapore Pte Ltd., Singapore, ISBN 978-981-10-7334-2.

[34] Guan, G., Kaewpanha, M., Hao, X., & Abudula, A. (2016). Catalytic steam reforming of biomass tar: Prospects and challenges. In Renewable and Sustainable Energy Reviews (Vol. 58, pp. 450–461). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.12.316

[35] Lyons Cerón, A.; Konist, A.; Lees, H.; Järvik, O. (2021). Effect of Woody Biomass Gasification Process Conditions on the Composition of the Producer Gas. Sustainability, *13*, 11763. https://doi.org/10.3390/su132111763

[36] Asadullah, M., Miyazawa, T., Ito, S., Kunimori, K., Yamada, M., & Tomishige, K. (2004). Gasification of different biomasses in a dual-bed gasifier system combined with novel catalysts with high energy efficiency. Applied Catalysis A-General - APPL CATAL A-GEN, 267, 95–102. https://doi.org/10.1016/j.apcata.2004.02.028

[37] McKendry, P. (2002). Energy production from biomass (part 3): gasification technologies. Bioresource Technology, 83(1), 55–63. https://doi.org/10.1016/S0960-8524(01)00120-1

[38] Motta, I. L., Miranda, N. T., Maciel Filho, R., & Wolf Maciel, M. R. (2018). Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects. In Renewable and Sustainable Energy Reviews (Vol. 94, pp. 998–1023). Elsevier Ltd. https://doi.org/10.1016/j.rser.2018.06.042

[39] Parthasarathy, P., & Narayanan, K. S. (2014). Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield - A review. In Renewable Energy (Vol. 66, pp. 570–579). Elsevier Ltd. https://doi.org/10.1016/j.renene.2013.12.025

[40] Sikarwar, V. S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M. Z., Shah, N., Anthony, E. J., & Fennell, P. S. (2016). An overview of advances in biomass gasification. In Energy and Environmental Science (Vol. 9, Issue 10, pp. 2939–2977). Royal Society of Chemistry. https://doi.org/10.1039/c6ee00935b

[41] Ramos, A., Monteiro, E., Silva, V., & Rouboa, A. (2018). Co-gasification and recent developments on waste-to-energy conversion: A review. In Renewable and Sustainable Energy Reviews (Vol. 81, pp. 380–398). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.07.025

[42] Ruiz, J. A., Juárez, M. C., Morales, M. P., Muñoz, P., & Mendívil, M. A. (2013). Biomass gasification for electricity generation: Review of current technology barriers. In Renewable and Sustainable Energy Reviews (Vol. 18, pp. 174–183). https://doi.org/10.1016/j.rser.2012.10.021

[43] Udomsirichakorn, J., & Salam, P. A. (2014). Review of hydrogen-enriched gas production from steam gasification of biomass: The prospect of CaO-based chemical looping gasification. In Renewable and Sustainable Energy Reviews (Vol. 30, pp. 565–579). https://doi.org/10.1016/j.rser.2013.10.013

[44] Bocci, E., Sisinni, M., Moneti, M., Vecchione, L., di Carlo, A., & Villarini, M. (2014). State of art of small scale biomass gasification power systems: A review of the different typologies. Energy Procedia, 45, 247–256. https://doi.org/10.1016/j.egypro.2014.01.027

[45] Hameed, Z., Aslam, M., Khan, Z., Maqsood, K., Atabani, A. E., Ghauri, M., Khurram, M. S., Rehan, M., & Nizami, A. S. (2021). Gasification of municipal solid waste blends with biomass for energy production and resources recovery: Current status, hybrid technologies and innovative prospects. Renewable and Sustainable Energy Reviews, 136. https://doi.org/10.1016/j.rser.2020.110375

[46] Sansaniwal, S. K., Pal, K., Rosen, M. A., & Tyagi, S. K. (2017). Recent advances in the development of biomass gasification technology: A comprehensive review. In Renewable and Sustainable Energy Reviews (Vol. 72, pp. 363–384). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.01.038

[47] Mishra, S., & Upadhyay, R. K. (2021). Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters. Materials Science for Energy Technologies, 4, 329–340. https://doi.org/10.1016/j.mset.2021.08.009

[48] Samiran, N. A., Jaafar, M. N. M., Ng, J. H., Lam, S. S., & Chong, C. T. (2016). Progress in biomass gasification technique - With focus on Malaysian palm biomass for syngas production. In Renewable and Sustainable Energy Reviews (Vol. 62, pp. 1047–1062). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.04.049

[49] Susastriawan, A. A. P., Saptoadi, H., & Purnomo. (2017). Small-scale downdraft gasifiers for biomass gasification: A review. In Renewable and Sustainable Energy Reviews (Vol. 76, pp. 989–1003). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.03.112

[50] Patra, T. K., & Sheth, P. N. (2015). Biomass gasification models for downdraft gasifier: A state-of-the-art review. In Renewable and Sustainable Energy Reviews (Vol. 50, pp. 583–593). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.05.012

[51] Watson, J., Zhang, Y., Si, B., Chen, W. T., & de Souza, R. (2018). Gasification of biowaste: A critical review and outlooks. In Renewable and Sustainable Energy Reviews (Vol. 83, pp. 1–17). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.10.003

[52] Dincer, I., & Bicer, Y. (2018). 1.27 Life Cycle Assessment of Energy. Comprehensive Energy Systems, 1–5, 1042–1084. https://doi.org/10.1016/B978-0-12-809597-3.00134-6

[53] International Organization for Standardization. (2006). Environmental management — Life cycle assessment — Principles and framework (ISO Standard No. 14040:2006). https://www.iso.org/standard/37456.html

[54] International Organization for Standardization. (2006). Environmental management — Life cycle assessment — Requirements and guidelines (ISO Standard No. 14044:2006). https://www.iso.org/standard/38498.html

[55] Lopes Silva, D. A., Nunes, A. O., Piekarski, C. M., da Silva Moris, V. A., de Souza, L. S. M., & Rodrigues, T. O. (2019). Why using different Life Cycle Assessment software tools can generate different results for the same product system? A cause–effect analysis of the problem. Sustainable Production and Consumption, 20, 304–315. https://doi.org/10.1016/j.spc.2019.07.005

[56] SimaPro | LCA software for informed changemakers. Available at: https://simapro.com/ Accessed: 02.10.2023.

[57] Product Sustainability Software and Data Suite | Sphera (GaBi). Available at: https://sphera.com/product-sustainability-software/ Accessed: 02.10.2023.

[58] OpenLCA.org | openLCA. Available at: https://www.openlca.org/ Accessed: 02.10.2023.

[59] Life Cycle Assessment (LCA) Software | Umberto. Available at: https://www.ifu.com/umberto/lca-software/ Accessed: 02.10.2023.

[60] Ozturk, M. U., Ayol, A., & Tezer, O. (2023). Life cycle assessment of olive pomace gasification for an up-draft fixed bed gasifier system. International Journal of Hydrogen Energy, 48(60), 23339–23347. https://doi.org/10.1016/j.ijhydene.2023.01.206

[61] Balcioglu, G., Jeswani, H. K., & Azapagic, A. (2023). A sustainability assessment of utilising energy crops for heat and electricity generation in Turkey. Sustainable Production and Consumption, 41, 134–155. https://doi.org/10.1016/j.spc.2023.08.003

[62] Nguyen, T. L. T., & Hermansen, J. E. (2015). Life cycle environmental performance of miscanthus gasification versus other technologies for electricity production. Sustainable Energy Technologies and Assessments, 9, 81–94. https://doi.org/10.1016/j.seta.2014.12.005

[63] Tonini, D., Hamelin, L., Wenzel, H., & Astrup, T. (2012). Bioenergy Production from Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including Land Use Changes. Environmental Science & Technology, 46(24), 13521–13530. https://doi.org/10.1021/es3024435

[64] Jeswani, H. K., Whiting, A., Martin, A., & Azapagic, A. (2019). Environmental and economic sustainability of poultry litter gasification for electricity and heat generation. Waste Management, 95, 182–191. https://doi.org/10.1016/j.wasman.2019.05.053

[65] Mohammadi, F., Roedl, A., Abdoli, M. A., Amidpour, M., & Vahidi, H. (2020). Life cycle assessment (LCA) of the energetic use of bagasse in Iranian sugar industry. Renewable Energy, 145, 1870–1882. https://doi.org/10.1016/j.renene.2019.06.023

[66] Parascanu, M. M., Kaltschmitt, M., Rödl, A., Soreanu, G., & Sánchez-Silva, L. (2021). Life cycle assessment of electricity generation from combustion and gasification of biomass in Mexico. Sustainable Production and Consumption, 27, 72–85. https://doi.org/10.1016/j.spc.2020.10.021

[67] Zang, G., Zhang, J., Jia, J., Lora, E. S., & Ratner, A. (2020). Life cycle assessment of power-generation systems based on biomass integrated gasification combined cycles. Renewable Energy, 149, 336–346. https://doi.org/10.1016/j.renene.2019.12.013

[68] Clodoveo, M. L., Camposeo, S., Amirante, R., Dugo, G., Cicero, N., & Boskou, D. (2015). 7 - Research and Innovative Approaches to Obtain Virgin Olive Oils with a Higher Level of Bioactive Constituents. In D. Boskou (Ed.), Olive and Olive Oil Bioactive Constituents (pp. 179–215). AOCS Press. https://doi.org/10.1016/B978-1-63067-041-2.50013-6

[69] Skaltsounis, A.-L., Argyropoulou, A., Aligiannis, N., & Xynos, N. (2015). 11 - Recovery of High Added Value Compounds from Olive Tree Products and Olive Processing Byproducts. In D. Boskou (Ed.), Olive and Olive Oil Bioactive Constituents (pp. 333–356). AOCS Press. https://doi.org/10.1016/B978-1-63067-041-2.50017-3

[70] Tezer, Ö., Karabağ, N., Öngen, A., & Ayol, A. (2023). Gasification performance of olive pomace in updraft and downdraft fixed bed reactors. International Journal of Hydrogen Energy, 48(60), 22909–22920. https://doi.org/10.1016/j.ijhydene.2023.02.088

[71] Espadas-Aldana, G.; Guaygua-Amaguaña, P.; Vialle, C.; Belaud, J.-P.; Evon, P.; Sablayrolles, C. (2021) Life Cycle Assessment of Olive Pomace as a Reinforcement in Polypropylene and Polyethylene Biocomposite Materials: A New Perspective for the Valorization of This Agricultural By-Product. Coatings, 11, 525. https://doi.org/10.3390/coatings11050525

[72] Kolowca, J. (2007). Analiza geometrii źdźbła miskanta olbrzymiego. Inżynieria Rolnicza, R. 11, nr 7 (95)(7 (95)), 87–92.

[73] Kotecki, A. (2010.). Uprawa miskanta olbrzymiego: energetyczne i poza energetyczne możliwości wykorzystania słomy. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu. http://www.dbc.wroc.pl/dlibra/publication/edition/18846

[74] Britannica, The Editors of Encyclopaedia. "pine". Encyclopedia Britannica, (2023), Available online: https://www.britannica.com/plant/pine. Accessed 04.10.2023.

[75] Venkat, N. Owlcation, Interesting Facts About Pine Trees, (2022), Available online: https://owlcation.com/stem/Interesting-Facts-About-Pine-Trees Accessed 04.10.2023.

[76] Stasiak, M., Molenda, M., Bańda, M. et al. Mechanical characteristics of pine biomass of different sizes and shapes. Eur. J. Wood Prod. 77, 593–608 (2019). https://doi.org/10.1007/s00107-019-01415-w

[77] Kacperczyk, G. (2006). Zasady metodyczne sprawozdawczości statystycznej z zakresu gospodarki paliwami i energią oraz definicje stosowanych pojęć. Główny Urząd Statystyczny https://stat.gov.pl/download/cps/rde/xbcr/gus/zasady_metodyczne_sprawozdawczosci_stat_paliw_2006.pdf

[78] Oluyede, E., & Phillips, J. (2007). Fundamental Impact of Firing Syngas in Gas Turbines (Vol. 3). https://doi.org/10.1115/GT2007-27385

[79] United States Environmental Protection Agency, Greenhouse Gas Inventory Guidance. Direct Emissions from Stationary. Combustion Sources. (2020). Available online: https://www.epa.gov/sites/default/files/2016-03/documents/stationaryemissions_3_2016.pdf Accessed: 18.08.2023.

[80] Hauschild, M.Z., Huijbregts, M.A.J. (2015). Introducing Life Cycle Impact Assessment. In: Life Cycle Impact Assessment. LCA Compendium – The Complete World of Life Cycle Assessment. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9744-3_1

[81] Database & Support team at PRé Sustainability. (2023). SimaPro database manual. Methods library. Available online: https://simapro.com/wp-content/uploads/2023/04/DatabaseManualMethods.pdf Accessed: 04.10.2023.

[82] Acero A., Rodríguez C., Ciroth A. (2016) LCIA methods: Impact assessment methods in Life Cycle Assessment and their impact categories. https://www.openlca.org/wp-content/uploads/2016/08/LCIA-METHODS-v.1.5.5.pdf

[83] Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. In International Journal of Life Cycle Assessment (Vol. 8, Issue 6, pp. 324–330). Springer Verlag. https://doi.org/10.1007/BF02978505

[84] Lourinho, G.; Alves, O.; Garcia, B.; Rijo, B.; Brito, P.; Nobre, C. Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation. Recycling 2023, 8, 49. https://doi.org/10.3390/recycling8030049

[85] IRENA. International Renewable Energy Agency. Renewable Energy technologies: cost analysis series. Biomass for Power Generation 2012.

[86] Cardoso, J., Silva, V., & Eusébio, D. (2019). Techno-economic analysis of a biomass gasification power plant dealing with forestry residues blends for electricity production in Portugal. Journal of Cleaner Production, 212, 741–753. https://doi.org/10.1016/j.jclepro.2018.12.054

[87] Hermoso-Orzáez, M.J.; Mota-Panizio, R.; Carmo-Calado, L.; Brito, P. Thermochemical and Economic Analysis for Energy Recovery by the Gasification of WEEE Plastic Waste from the Disassembly of Large-Scale Outdoor Obsolete Luminaires by LEDs in the Alto Alentejo Region (Portugal). Appl. Sci. 2020, 10, 4601. https://doi.org/10.3390/app10134601

[88] Borello, D.; Pantaleo, A.M.; Caucci, M.; De Caprariis, B.; De Filippis, P.; Shah, N. Modeling and Experimental Study of a Small-Scale Olive Pomace Gasifier for Cogeneration: Energy and Profitability Analysis. Energies 2017, 10, 1930. https://doi.org/10.3390/en10121930

[89] Dawson, D. Oilve Oil Times. Olive Oil Production in Portugal Set to Slump After Record Year (2022). Available Online: https://www.oliveoiltimes.com/production/olive-oil-production-in-portugal-set-for-slump-after-record-year/111817 Accessed: 20.08.2023.

[90] Lee, U., Han, J., & Wang, M. (2017). Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. Journal of Cleaner Production, 166, 335–342. https://doi.org/10.1016/j.jclepro.2017.08.016

[91] Witzel, C.-P., & Finger, R. (2016). Economic evaluation of Miscanthus production – A review. Renewable and Sustainable Energy Reviews, 53, 681–696. https://doi.org/10.1016/j.rser.2015.08.063

[92] Boakye-Boaten, N. A., Kurkalova, L., Xiu, S., & Shahbazi, A. (2017). Techno-economic analysis for the biochemical conversion of Miscanthus x giganteus into bioethanol. Biomass and Bioenergy, 98, 85–94. https://doi.org/10.1016/j.biombioe.2017.01.017

[93] Meyer, P. A., Snowden-Swan, L. J., Jones, S. B., Rappé, K. G., & Hartley, D. S. (2020). The effect of feedstock composition on fast pyrolysis and upgrading to transportation fuels: Techno-economic analysis and greenhouse gas life cycle analysis. Fuel, 259, 116218. https://doi.org/10.1016/j.fuel.2019.116218

[94] Electricity price statistics - Statistics Explained. Electricity Price Statistics - Statistics Explained. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers Accessed: 20.08.2023

[95] Statista Research Department (2023) Portugal: monthly electricity prices 2023 Available online: https://www.statista.com/statistics/1281464/portugal-monthly-wholesale-electricity-price/ Accessed: 20.08.2023

[96] Zhang, N., Hoadley, A., Patel, J., Lim, S., & Li, C. (2017). Sustainable options for the utilization of solid residues from wine production. Waste Management, 60, 173–183. https://doi.org/10.1016/j.wasman.2017.01.006

[97] Shabangu, S., Woolf, D., Fisher, E. M., Angenent, L. T., & Lehmann, J. (2014). Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts. Fuel, 117, 742–748. https://doi.org/10.1016/j.fuel.2013.08.053

[98] Castro, R. (2022). Electricity Production from Renewables. In Electricity Production from Renewables. Springer International Publishing. https://doi.org/10.1007/978-3-030-82416-7

[99] Mohr, C. H., Coppus, R., Iroumé, A., Huber, A., & Bronstert, A. (2013). Runoff generation and soil erosion processes after clear cutting. Journal of Geophysical Research: Earth Surface, 118(2), 814–831. https://doi.org/10.1002/jgrf.20047

[100] Weger, J.; Knápek, J.; Bubeník, J.; Vávrová, K.; Strašil, Z. Can Miscanthus Fulfill Its Expectations as an Energy Biomass Source in the Current Conditions of the Czech Republic? —Potentials and Barriers. Agriculture 2021, 11, 40. https://doi.org/10.3390/agriculture11010040

[101] Gordon, T., Stanek, L. W., & Brown, J. (2014). Pollution, Air in Encyclopedia of Toxicology. In P. Wexler (Ed.), Encyclopedia of Toxicology (Third Edition) (pp. 995–1002). Academic Press. https:/doi.org/10.1016/B978-0-12-386454-3.00530-3

[102] Khalaf EM, Mohammadi MJ, Sulistiyani S, Ramírez-Coronel AA, Kiani F, Jalil AT, Almulla AF, Asban P, Farhadi M, Derikondi M. Effects of sulfur dioxide inhalation on human health: a review. Reviews on Environmental Health, 2022. https://doi.org/10.1515/reveh-2022-0237

[103] Morrissey, C. A., Dods, P. L., & Elliott, J. E. (2008). Pesticide treatments affect mountain pine beetle abundance and woodpecker foraging behavior. Ecological Applications, 18(1), 172–184. https://doi.org/10.1890/07-0015.1

[104] Timilsina, Govinda R.. 2020. Demystifying the Costs of Electricity Generation Technologies. Policy Research Working Paper;No. 9303. © World Bank, Washington, DC. http://hdl.handle.net/10986/34018

[105] IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi.

[106] Narnaware, S. L., & Panwar, N. L. (2022). Biomass gasification for climate change mitigation and policy framework in India: A review. Bioresource Technology Reports, 17, 100892. https://doi.org/10.1016/j.biteb.2021.100892

[107] Caputo, A. C., Palumbo, M., Pelagagge, P. M., & Scacchia, F. (2005). Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass and Bioenergy, 28(1), 35–51. https://doi.org/10.1016/j.biombioe.2004.04.009

[108] Zahab, Z. (2022). GTI Energy. Challenges for Biomass Gasification to Fuels and Chemicals. Available online: https://www.energy.gov/sites/default/files/2022-12/beto-02-gasification-wkshp-nov-2022-elzahab.pdf Accessed 22.09.2023

[109] Dogu, O., Pelucchi, M., van de Vijver, R., van Steenberge, P. H. M., D'hooge, D. R., Cuoci, A., Mehl, M., Frassoldati, A., Faravelli, T., & van Geem, K. M. (2021). The chemistry of chemical recycling of solid plastic waste via pyrolysis and gasification: State-of-the-art, challenges, and future directions. Progress in Energy and Combustion Science, 84, 100901. https://doi.org/10.1016/j.pecs.2020.100901

[110] Roudneshin, M., & Azadeh, A. (2019). A novel multi-objective fuzzy model for optimization of oil sludge management by considering Health, Safety and Environment (HSE) and resiliency indicators in a gas refinery. Journal of Cleaner Production, 206, 559–571. https://doi.org/10.1016/j.jclepro.2018.09.142

[111] Huang, J.; Schmidt, K.G.; Bian, Z. Removal and Conversion of Tar in Syngas from Woody Biomass Gasification for Power Utilization Using Catalytic Hydrocracking. Energies 2011, 4, 1163-1177. https://doi.org/10.3390/en4081163

[112] Xiao, X., Cao, J., Meng, X., Le, D. D., Li, L., Ogawa, Y., Sato, K., & Takarada, T. (2013). Synthesis gas production from catalytic gasification of waste biomass using nickel-loaded brown coal char. Fuel, 103, 135–140. https://doi.org/10.1016/j.fuel.2011.06.077

[113] He, Q., Guo, Q., Umeki, K., Ding, L., Wang, F., & Yu, G. (2021). Soot formation during biomass gasification: A critical review. Renewable and Sustainable Energy Reviews, 139, 110710. https://doi.org/10.1016/j.rser.2021.110710

[114] Namioka, T., Yoshikawa, K., Hatano, H., & Suzuki, Y. (2003). High Tar Reduction with Porous Particles for Low Temperature Biomass Gasification: Effects of Porous Particles on Tar and Gas Yields during Sawdust Pyrolysis. JOURNAL OF CHEMICAL ENGINEERING OF JAPAN, 36(12), 1440–1448. https://doi.org/10.1252/jcej.36.1440

[115] Buragohain, B., Mahanta, P., & Moholkar, V. S. (2010). Biomass gasification for decentralized power generation: The Indian perspective. Renewable and Sustainable Energy Reviews, 14(1), 73–92. https://doi.org/10.1016/j.rser.2009.07.034

[116] Miedema, J.H.; Van der Windt, H.J.; Moll, H.C. Opportunities and Barriers for Biomass Gasification for Green Gas in the Dutch Residential Sector. Energies 2018, 11, 2969. https://doi.org/10.3390/en11112969

[117] Chambon, C. L., Karia, T., Sandwell, P., & Hallett, J. P. (2020). Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India. Renewable Energy, 154, 432–444. https://doi.org/10.1016/j.renene.2020.03.002